USGS Software for Probabilistic Seismic Hazard Analysis (PSHA)
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Introduction and Overview

Software for running probabilistic seismic hazard analysis (PSHA) is available from several companies, and open-source software is available from a few government agencies. The USGS PSHA codes are open-source software.

There are advantages to deciding to work with PSHA software from any particular vendor and there are advantages to using open-source software, or freeware. No PSHA software is particularly easy to use, so all users should expect to have to spend some time learning the scope and limits of any given code or set of codes. A disadvantage of freeware is that support for new users is very limited. This documentation is pretty much the extent of support for USGS PSHA software, for example.

The USGS in Golden Colorado has been performing PSHA since the 1970s and has been distributing versions of PSHA software since the 1980s. The National Seismic Hazard Mapping Project has the task of updating the National Seismic Hazard Map every three to five years, incorporating new ideas about sources, source-to-site attenuation, and site response with each update. The USGS in Golden Colorado has been using Fortran to build its PSHA models. We switched from Fortran-77 to Fortran-95 in recent years. Fortran-95 is the language of gfortran, which is a freely available compiler that has been installed or can be installed on many personal computers (PCs). We have tested our programs with a gfortran compiler. One advantage of Fortran-95 is that it can be optimized to run large sets of hazard calculations at very high speed. This means that national-scale hazard maps can be computed in reasonably short time periods. Some other computer languages are probably just as fast, but we know of none that are faster.

In 2007, the USGS is in the middle of an update cycle. All PSHA software has been extensively revised for this 2007 update. These revised codes are made available here.

Revisions are Important

Research is constantly resulting in new and increasingly sophisticated models of the seismic source and seismic wave amplification and attenuation. In 2007, some of the important revisions to USGS software include:
- clustered-event hazard
- improved distance computations for random sources
- improved distance estimation for known faults
- faster, more accurate numerical algorithms
- many new attenuation models for subduction, deep intraplate, and crustal sources
- improved site response estimation, including continuous Vs30 and nonlinear site response for many attenuation models
- more extensive quality assurance testing
- more useful log files
- testing on different computer platforms, Sun Solaris, Windows PC, Linux PC.

Types of Sources in PSHA

Three broad classes of earthquake sources are defined in USGS PSHA: (1) Subduction sources, (2) background or gridded sources, and (3) crustal fault sources. Each class has its own PSHA software, so it is important to know from the start to which category each earthquake source belongs.

Background sources are the most abstract or nebulous class. USGS PSHA software has a variety of treatments for background sources. Is the strike known or unknown? Fixed-strike background sources can be modeled if the strike of background earthquakes is believed to be known. Otherwise, background sources are considered to be point sources up to magnitude 6, and are random strike for magnitude ≥ 6. Their lengths are governed by a relationship, that of Wells and Coppersmith, that predicts fault length from magnitude.

The depth of background seismicity is another issue of interest. USGS software allows one, two, or three depths, with relative frequencies specified. Smaller sources can have a different depth, frequency distribution than larger ($M \geq 6.5$) sources. The current version of USGS software does not have geographically varying depth distribution. If you want to model geographic variation of source depth, you will need to run the code multiple times, assigning different depth distributions in different geographic regions.

Deep sources, those within the subducting oceanic plate, or Benioff Zone sources, have their own attenuation models. These sources are always considered background sources, because we have no specific fault information for them. When modeling hazard from deep sources, they can have fixed or random strike.

Types of Attenuation Models in PSHA

Attenuation models are broadly grouped into about four classes: (1) subduction source models, (2) deep intraplate or Benioff zone sources, (3) low-Q, or high attenuation models, associated with seismicity in tectonically active regions, such as the western United States (WUS), and (4) high-Q, or low attenuation models, associated with seismicity in tectonically stable regions, such as the Central and Eastern United States (CEUS).

Within a given software code, each attenuation model that is currently available is assigned a specific index. The indexes are small integers, usually in the range 1 to 30, but some have negative values. Negative indexes always indicate a special site class, hard rock for some models, and soft soil for others. Positive indexes for older relations tend to correspond to a site class that the USGS uses as a standard for preparation of its national seismic hazard maps. This is the BC site class, rock with Vs30 at the border between the B-class and the C-class.

The attenuation model indexes are given in sections that follow and are also defined in the comment lines near the beginning of the source code listings.

Site Conditions and Site Classes

Attenuation models may also be categorized by how they handle site response, which is always of great interest to the engineering community whose goal is seismic-resistant design. There has been a rapid evolution in the level of sophistication of treatment of site response in the last two decades. Earlier models, those of the 1980s for example, tended to deal with a limited range of site categories, such as soft soil and firm rock. Then, in the mid- to late-1990s, more categories were modeled, such as soft soil, firm soil, firm rock, and hard rock. These categories often paralleled or were equivalent to the NEHRP site classes: A, B, C, D, and E. Now, many ground-motion relations include a soil model in which site response varies continuously with the average shear-wave velocity in the upper 30 m of soil under the site, or Vs30. Generally, newer relations include a nonlinear site response, in which shorter period oscillations are damped more (or amplified less) as the level of rock PGA increases. This soil-response feature, while known for many years to geotechnical analysts, was a bit slow to percolate into widely used PSHA attenuation models. Now, in 2007, such awareness is commonplace and is a part of all of the Next Generation of Attenuation, or NGA models, for example.

The software user needs to be aware of the capabilities and limits of the ground-motion attenuation models that he or she wishes to use in the PSHA. For example, if the analysis calls for ground motions that are tuned to a specified Vs30 rather than a broad site class, some relations might not be as suitable as others. Often, users have adopted rational strategies for modeling site classes of interest. For example, hazard curves corresponding to a firm soil site class might be approximated by running soft-soil and firm-rock analyses and averaging the hazard curves from these two models.

PSHA Rules

Many mathematical rules must be adhered to when performing PSHA. These rules are summarized in PSHA textbooks and articles. One of the most frequently used rules in PSHA is the law of expected value:

$$E\left[\sum X\right] = \sum E\left[X\right]$$

This law of mathematical probability is the basis for combining hazard curves from different source and attenuation models. Thus, if the mean rate of ground-motion exceedances from model 1 is r_1 and from model 2 is r_2, the mean rate from one or the other (or both) is $r_1 + r_2$. The PSHA application of this law is always with respect to conditional expectation, that is, the rate of exceedance conditioned on different source and attenuation model properties. The law for conditional expectation continues to look like the above equation. X is a rate of events, and is not a probability. The above formula does not apply to probability. For example, the above formula could yield a number greater than 1, meaning more than one ground-motion exceedance per year, whereas a probability cannot exceed one. P(E)=1 corresponds to the certain event. P(E)>1 is a mathematical and logical error.

Compiling F95 codes

SUN computers with Solaris:
Our most extensive experience is with SUN computers with Solaris OS. We have been running PSHA codes on Solaris machines and on similar DEC-alpha machines for two decades. On Sun Solaris, we use f95. A compile instruction is:

f95 hazcode.f iosubs.o –e –fast –o hazcode

The –e instruction is to extend line-length beyond the standard fortran limit (column 72). The –fast instruction is to optimize the mathematics. The object code iosubs.o is for input/output of binary files. You should also try compiling with –C to check subscript-range bounds and errors, if you are concerned about new input files with bigger than usual region or more than usual number of models to combine.

Personal Computers (PCs):
Our experience is less extensive here. We first succeeded in porting the SUN software to a PC-cluster with a Linux-like operating system. This was the motivation to go from f77 to f95, because the gfortran compiler recognized f95 constructs such as type but not f77 constructs such as structure.

We then began compiling the hazard codes on PCs with modern Windows XP operating systems. We use gfortran here as well. Compile flags can be tricky:

gfortran hazcode.f –static –O –ffixed-line-length-none –ffpe-trap= -o hazcode.exe iosubs.o
or
gfortran hazcode.f –static –O –ffixed-line-length-none –ffpe-trap= -o hazcode.exe iosubs.o –finit-local-zero

The iosubs.o routines would have been compiled on the PC as well. The –O flag is supposed to optimize the run, like the –fast flag on the SUN solaris machines. The –finit-local-zero flag is a relatively recent addition to gfortran. It initializes variables that were not explicitly initialized to zero and, in the case of logical variables, .false. This flag is useful because the SUN compilers (f77, f95) have been making this implicit initialization.

On PCs with Linux OS, the gfortran with –O seems to work properly. We admit that this limited experience is less than satisfactory, but that is what we know as of June 28, 2007. Note added Nov, 2008: The latest gfortran versions, later than Feb 2008 seem to have overcome problems with –O and so on. You should be able to use this flag if you have downloaded a recent gnu fortran package.

Codes to Prepare Input Files

For gridded hazard.

Chuck Mueller working on this. How do we prepare rate matrices (agrids) from earthquake catalogs? Program is *agridMLsm.f*.

Another program is called *amakeshear.f*. This program is given a polygon's vertices, a seismogenic crustal width, and a slip-rate (units: mm/yr). It defines a plane with specified depth and strike along the long-axis of the polygon, computes the moment rate on that virtual plane, and writes a-values that correspond to redistribution of that moment over the grid of source points within the polygon using a truncated GR distribution. Optionally, *amakeshear.f* can smooth the resulting agrid to lap over the edges of the polygon rather than terminate abruptly thereon. This program has been used to prepare fixed-strike shear zones in California and Nevada, as well as in the Puget Sound region of northwest Washington. The basic motivation is that a portion of the slip rate that is inferred from GPS data but that is not reflected in earthquake catalogs (seismicity less than geodetically inferred hazard) is inserted into the hazard model in these shear zones. The other portion is assumed to dissipate aseismically.

Another code is used to compute mean distance from an unknown fault with random strike. This code is called *getmeanrjf.f*. This code allows you to choose an option for converting fault magnitude to fault rupture length. The mean or average distance to site is a function of this rupture length. More compact ruptures will in general tend to be further from a given site than more sprawling ruptures that are associated with a given size or magnitude. The output of this program is explicitly named in input files to later versions (4 and later) of the hazgridXnga codes.

For faults.

The program for converting fault information supplied by geologists to input file format for the hazard code is called *fltrate.v2.f*.

Fault information collected by geologists in the field must include a fault name and/or identifier, the sampled location (longitude, latitude) of each fault trace, described as a series of points, and the sense-of-slip indicator, which is 1 for strike slip, 2 for reverse or 3 for normal slip. Also, the fault dip (an average value works fine), the slip rate (for strike-slip sources) or uplift rate (for dip-slip sources), the minimum and maximum magnitude of event that is plausible to associate with this fault. The top-of-fault depth, which is 0 for daylighting or surface-rupturing faults, *k* km for blind thrust or blind normal faults, the fault width, and perhaps other information, is needed. Other information includes a preferred rate of events, which may determined from historical and paleoseismic records. This preferred rate can be used instead of or in addition to the rate that is computed from slip rate and seismological principles. A sample input file (blue) to *fltrate.v2.f* and sample run output (green and brown) is included below.

```
#Line 1 - ID,NAME -
#Line 2SLIPRATE,SENSE,LENGTH,DIP,TOP,BOTTOM,WIDTH,#MAGS,M_CHAR,WEIGHT -
#LINE 3 - number of POINTS - LINES4+ - LONG LAT pairs
1. 6.5 0.1        1= b-value, 6.5=mmin, 0.1=dM
1,Thoen fault
0.6,3,106.646514,50,0,15,19.5811093,1,7.43,1
9
99.8127199999999,18.2639199999994
99.7484700000005,18.1770699999997
```

```
99.6996799999997,18.10844
99.5810899999997,18.0411399999994
99.57042,18.01505
99.4593700000005,17.9308000000001
99.3547099999996,17.7852899999998
99.3066799999997,17.6652200000008
99.2023800000006,17.5262899999998
2,Long fault
0.1,3,63.206062,50,0,15,19.5811093,1,7.17,1
6
99.4767400000001,17.8202799999999
99.5757599999997,17.9074400000009
99.6350500000008,17.9738500000003
99.7257699999991,18.0295800000004
99.8313099999996,18.1161499999998
99.9232200000006,18.1950099999995
```

The program *fltrate.v2.f* accepts one input file plus some interactive input from the computer monitor. Before fault information, the input file contains some general information, first some header lines that describe the data. These are optional but must begin with the '#' character. The next general information, to be used with all faults to follow, are some parameters for Gutenberg Richter models, here 6.5 as *Mmin*, 1 as the *b-value* to assume, and 0.1 as a possible *dM* to use. The input file next contains *nflt* fault descriptions. In the above example, *nflt*=2, named the Thoen fault and the Long fault, respectively. For the Thoen fault, the annual uplift rate is 0.6 mm/yr, the slip type is normal (sense of slip 3), the length is about 106 km (this will be recomputed in fltrate.v2, so your input length does not need to be too accurate), the dip is 50º, the fault top is at 0 km depth, the bottom at 15 km, the fault width is about 19.6 km, the number of magnitudes is 1, M is 7.43, and the weight to be applied is 1.0. Unless instructed otherwise the code will recomputed this magnitude so the value in the input does not need to be too accurate. The fault location is described by 9 longitude,latitude pairs, which follow the 9. In this case the geologist has given us location pairs with lots of decimal places. Sampled fault coordinates don't need accuracy to better than 50 m in most cases. It may be important to sample fault locations where the strike changes more than a few degrees. After Thoen, the Long fault is similarly described. If the geologist enters a negative number for the slip rate, the code will ask you the rate of earthquakes you want to use in you model for each such fault. This rate might be based on historical catalog rates of earthquakes on this fault rather than on slip rate. For example, if there were 5 such characteristic events in the 20th century, you could manually enter an annual rate of 0.05 (i.e., 5/100, but don't enter this value as a fraction – the code wants a decimal number here) when the computer prompts you for rate information. Generally the historical record is not extensive enough to provide reliable event-rate information, but if a combination of historical data and trenching data is available, and if the geologist believes these data are superior to slip-rate information, the best estimate should be used. You can use multiple rate estimates with different weights corresponding to your preference for the various models. These become logic-tree branches and branch weights.

A successful run of this code produces two or three primary output files, one for characteristic sources with M>6.5, one for Gutenberg-Richter sources with M>6.5, and

the third, for characteristic sources with M≤6.5, if there are any. Some other summary data files may also be written. For the above (blue) input file, two output files were written. These are now shown (green is characteristic-source file color, brown is GR source file color):

```
1 3 1 1     1,Thoen fault
 7.43 3.1318672E-4 1.0
 50.0 19.58112 0.0E+0 106.646514
 9
       18.26392          99.81272
       18.17707          99.74847
       18.10844          99.69968
       18.04114          99.58109
       18.01505          99.57042
       17.93080          99.45937
       17.78529          99.35471
       17.66522          99.30668
       17.52629          99.20238
 1 3 1 1     2,Long fault
 7.17 7.593876E-5 1.0
 50.0 19.58112 0.0E+0 63.206062
 6
       17.82028          99.47674
       17.90744          99.57576
       17.97385          99.63505
       18.02958          99.72577
       18.11615          99.83131
       18.19501          99.92322


2 3 1 1     1,Thoen fault
 3.234987 1.0 6.5 7.43 0.11624998 1.0
 50.0 19.58112 0.0E+0 106.646514
 9
       18.26392          99.81272
       18.17707          99.74847
       18.10844          99.69968
       18.04114          99.58109
       18.01505          99.57042
       17.93080          99.45937
       17.78529          99.35471
       17.66522          99.30668
       17.52629          99.20238
 2 3 1 1     2,Long fault
 2.4293975 1.0 6.5 7.17 0.11166668 1.0
 50.0 19.58112 0.0E+0 63.206062
 6
       17.82028          99.47674
       17.90744          99.57576
       17.97385          99.63505
       18.02958          99.72577
       18.11615          99.83131
       18.19501          99.92322
```

In the above example the rate of characteristic events for the Thoen fault is `3.1318672E-4` and for the Long fault the rate is `7.593876E-5`. Similar rate information may be

found for these faults in the GR file. 3.13E-4 is computer-code jargon for $3.13 \cdot 10^{-4}$, which corresponds to a mean recurrence time of about 3200 years. This fault ruptures too infrequently to have much influence on the 2% in 50 year hazard map (which corresponds to a 2500 year return time). The Long fault is even less active. The GR distribution has more frequent earthquake occurrences, and even though these earthquakes are lower magnitude than the characteristic ruptures, they tend to produce more hazardous ground motions. An example calculation for the Thoen fault is, frequency of M6.5 = 10^{a-bM} =$10^{3.234987- 6.5}$ = 0.000543, for a mean recurrence interval of 1841 years. The full sequence of GR events with 6.5 < M < Mchar = 7.43 has a somewhat shorter recurrence interval than 1840 years. Model sensitivity to these GR ruptures shows us that the decision about the fraction of available seismic moment that is to be assigned to GR-distributed sources on each fault is important.

The first two files (for M>6.5 sources) are often thought of as corresponding to alternative models, and are often given weights that sum to one. The idea of using alternate models is that we don't know whether future earthquakes will be large fault-filling ruptures or smaller ruptures which only occupy a relatively small portion of the fault. Weights should be based on the analyst's preference for characteristic or Gutenberg Richter rupture processes which ideally is based on seismological, geological and historical information. If you are indifferent to these competing models, you may give each a weight of 0.5 when you combine their hazard curves. For M<6.5 earthquakes, USGS software assumes only characteristic rupture. The determination of magnitude from the input fault information is based on a Surface-Rupture-Length, Magnitude relation developed by Wells and Coppersmith (BSSA, 1994). Certain overrides are also possible. These include a minimum magnitude to model (often 6.5) and a maximum magnitude to model. We allow two maximum magnitudes, one for long strike-slip faults, and one, typically having a lower Mmax, for dip-slip faults. We have used M8 as a typical upper limit for strike-slip source magnitude, where no historical information is otherwise available to inform our estimate, and M7.5 for dip-slip sources. These limits should be determined by seismologists and geologists who are experts in the regional tectonics. Historical magnitudes on the fault are uncertain but if trusted should not be larger than the Mmax assigned to the fault for the PSHA characteristic-source model. Another limit on faults is total length. The hazard code *hazFXnga7c* currently can work with faults having a maximum length of about 960 km.

The program *fltrate.v2.f* will output fault information suitable for input to *hazFXnga7c* (or other programs in the hazFX family) until it reaches an end-of-information (end-of-file) mark or invalid input. The user needs to look at the log file or information on the computer monitor to see if there was an error in the input data. Such errors cause the code to issue a one-line warning and stop. This warning is all that you will see so it is necessary to establish that the output files contain all of the fault information that you expect, i.e., corresponding to all of the faults that were in the input. If not, you must correct the input file at its offending line or lines and rerun until the code execution stops at end-of-information.

Before the output of *fltrate.v2.f* is suitable to input to a *hazFX* code, header information must be attached to the file. This header information tells the program what region (or set of sites) will be analyzed, what spectral periods will be considered, and what attenuation models will be used. A few other parameters, such as the value of Vs30 to use, are also defined in this header file. Here is an example header file that could be used with the brown file above (the GR sources):

```
0        ! grid of sites, use hazFXnga7c (or x). GR distributed M
0.0 22. 0.1   6/08/2007 revised
94. 105. .1
760. 3. !vs30 and depth to hardrock (vs 2500 m/s)
1. 200.
3 !number of spectral periods
0. 0 0 PGA
thaipga.gr.lowQ
19
.005 .007 .0098 .0137 .0192 .0269 .0376 .0527 .0738 .103 .145 .203 .284
.397 .556 .778 1.09 1.52 2.13
3
13 0.333 1000. 1 0 B and A, NGA
14 0.333 1000. 1 0 C and B, NGA
15 0.334 1000. 1 0 C and Y, NGA
0.2 0 0 sec PSA
thai5hz.gr.lowQ
19
.005 .0075 .0113 .0169 .0253 .0380 .0570 .0854 .128 .192 .288 .432 .649
.973 1.46 2.19 3.28 4.92 7.38
3
13 0.333 1000. 1 0 B and A, NGA
14 0.333 1000. 1 0 C and B, NGA
15 0.334 1000. 1 0 C and Y, NGA
1.0 0 0 sec PSA
thai1hz.gr.lowQ
20
.0025 .00375 .00563 .00844 .0127 .0190 .0285 .0427 .0641 .0961 .144
.216 .324 .487 .730 1.09 1.64 2.46 3.69
 5.54
3
13 0.333 1000. 1 0 B and A, NGA
14 0.333 1000. 1 0 C and B, NGA
15 0.334 1000. 1 0 C and Y, NGA
1. 1.
1
0
1
0 1
```

The above header gives hazFXnga7c the information to find hazard in a region that covers much of Thailand, Malaysia, Myanmar, and Sumatra. It says to assume a Vs30 of 760 m/s at all sites, a depth to bedrock of 3 km, and to perform the analysis for PGA, for 1-s SA, and for 0.2-s SA (5 Hz). For each of these, use the attenuation models with

indexes 13, 14, and 15, and give them equal weight (1/3). The 200 on line 5 says to compute the hazard for source-to-site distance ≤ 200 km.

The last several lines in the above example tell the code not to branch on magnitude uncertainty beyond that which is specified in the input-file source list. The code is set up to allow both epistemic and aleatory branching on M, and the last 4 brown lines above can be modified to model these uncertainties. If you want to model magnitude epistemic uncertainty with dM=0.1 and further aleatory tails on these branches, you could use these as the last 4 lines:

3
-0.1 0 0.1
0.2 0.6 0.2
.12 3

The first of these lines say to define 3 magnitude branches. The next line says that the branch magnitudes are M-0.1, M, and M+0.1, respectively. The third line says that the weights for these three M values are 0.2, 0.6, and 0.2, respectively. The 4th line says to make a normal (bell-shaped) distribution about each central M value, with samples at M-0.15, M-0.1, M-0.05, M, M+0.05, M+0.1, and M+0.15, that is three samples on each side of the central M value. Their weights are given by the ordinates of a normal density function with σ (sigma) of 0.12. The 0.05 step is built into the source code. For the epistemic branches, the code determines event rates to give the same moment rate on the side branches as on the central branch. This moment-conserving assumption produces a skewed event rate. For the aleatory M resampling, the code re-distributes the moment among the several branches, but leaves branch event rates fixed. These details are taken care of in the source code.

For subduction sources.

There is no software for preparing input files for subduction sources. The main difference between the input for subduction or interface earthquakes and crustal fault earthquakes is that the subduction zone must be defined by a top-of-zone and a bottom-of-zone contour, whereas faults are defined by top-of-fault and fixed width. Fault contours are defined by *n* points along strike. The bottom of subduction is the location where elastic wave propagation from sliding friction ceases to occur; then, below this depth, the rock rheology is believed unsuitable (too hot basically) for stick-slip behavior. Of course subduction continues well into the Earth's mantle, but little seismic hazard is associated with deep subduction. Deformation of the subducting slab at depth may have seismic hazard; if so, it is categorized as deep background seismicity (see Types of Sources, above).

Uncertainty in top or bottom of subduction location is modeled by varying the locations of the slab contours and rerunning the subduction hazard code with these different source locations. Each subduction model must be run separately. In contrast, as many fault sources may be combined into one input file as is necessary, up to a maximum of 500 faults.

We next go into some detail on how to run the three main hazard programs, hazgridXnga2, hazFXnga7c, and hazSUBXnga.

HazgridXnga2.f and Later Versions

The first major seismic-hazard program in this package is hazgridXnga2.f, a program used for computing seismic hazard from background or gridded sources. Background sources can be categorized into two broad groups: (1) shallow and (2) deep. Shallow refers to events in the continental crust, generally less than 20 km deep. Deep refers to events within the subducting oceanic slab, or Benioff zone. These are often called intraplate events, and are distinguished from interplate events, which are discussed below in the section with hazSUBXnga.f. Intraplate event hypocenters typically range from about 50 km to about 100 km. They are sometimes deeper and sometimes shallower, depending on the geometry and geology of the subducting slab.

Different attenuation models are used to estimate ground motion from shallow and deep events. In hazgridXnga2, many attenuation models are available for shallow events, but only a few are available for deep events. Currently, we have models from Atkinson and Boore, from Geomatrix, and from Kanno for modeling deep intraplate events. Deep-event attenuation models often have a term associated with hypocenter depth, which often saturates at about 100 km. Shallow attenuation models often have a term that also increases or turns on for buried or blind sources. This is an NGA innovation. HazgridX allows for a distribution of depths for a given run. You can define up to three depths of sources. Depth in this context refers to depth of top of fault or virtual fault, not to hypocenter depth although for point sources, these are the same. Normally, because the sources are not mapped and are known only by seismicity catalogs or rates in the region, you would not specify zero depth as one of the alternatives. If a fault ruptures to the surface, it is presumably mapped by geologists, and its hazard is modeled with hazFXnga or a similar program.

For shallow events, we can group attenuation models by geographic applicability. In the United States we generally consider two broad sub-regions, tectonically active western North America (TNA), and tectonically relatively quiet eastern North America. We generally call TNA the low-Q region and CEUS the high-Q region. However, careful study of the attenuation models associated with these two regions shows that many WUS models have lower rates of attenuation with distance than some models that were developed for the CEUS. There are of course many attenuation models for Europe and Asia, such as Ambraseys models, that we have not coded into hazgridXnga (or the other USGS programs). The user should decide if the available set is adequate, or if other models need to be brought into the source code.

HazgridXnga2 uses a fixed site condition model, or Vs30, in contrast to the companion programs, hazFXnga7c and hazSUBXnga. There is a reason for this contrast. HazgridXnga2 has a computation strategy that computes the hazard curves for a fixed set of M and R(distance) before it actually works with the particular sites being investigated. For the sites being investigated, the hazard curve corresponding to the M and R nearest

those in the pre-computed array is selected. This approach has been used by USGS-Golden for many years, and was continued during the 2007 update, because this approach was found to be much faster than other alternatives.

 The user manual for this code follows. The available attenuation models are listed in the user manual. These models are also listed in the source-code comment lines, which should be read to learn many other things about the code.

HazgridXnga5: This code replaces *hazgridXnga2* and other earlier versions. The main input-file difference is the explicit inclusion of a line specifying the file that contains information on distance from site to a randomly-oriented vertical finite source (see the red line in below example). This file can be generated from software that uses different models of fault length as a function of magnitude, thus yielding different distances. A second alternative that could appear on this line is a fixed-strike file name. The fixed-strike file contains an array of virtual fault strikes (units: radians) on the same grid as the source array is defined. In earlier versions and in *hazgridXnga5*, setting iflt=2 means that fixed-strike angle is input on this line (units: degrees) and this same angle would be used for all sources. Now, setting iflt=-2 means that a field of strike values is input (binary file, units: radians). These strikes can represent preferred directions based on *a priori* information about different tectonic provinces styles of faulting or strain field.
A sample fortran program that writes the fixed-strike file is called *azimuth_to_pole.f*. In that program, fault strikes are determined based on location relative to a GPS Euler pole in Idaho. This option has had limited testing, and should be used with caution. A few other improvements have also been coded, including more elaborate soil models for the Geomatrix deep-source attenuation model.

PSHA Software Documentation

Program: hazgridXnga2.f
Language: fortran95 (gfortran)
Purpose: Compute probabilistic seismic hazard at various sites from a grid of earthquake sources
Current Technical Contact: Stephen Harmsen, harmsen@usgs.gov
Date of last Modification: June 10, 2007

To run: hazgridXnga2.exe input.file > log.file

Sample Input File: Black numbers are data values. Comments are given in blue. These blue comments are not read by the program. The data on the left side are what the program needs. Here is an example input file (red items for hazgridXnga5 only):

0   !use grid-of-sites option (1 implies list of stations)
0 22. 0.1   !minlat, maxlat,dlat Site grid includes Thailand&Indones.
94. 105. 0.1   !minlong, maxlong, dlong (in degrees)
760. 1   !Vs (m/s) in upper 30 m, 760 m/s here; depth (km) to rock having Vs of 2500 m/s
1 5.0 1 1   !depth to top-of-rupture distribution. Here, 1 depth; fix all events with top of rupture at 5 km depth
1 0 0   !proportion of Strike-slip, reverse, normal-faulting, resp.
5. 1000.   !delta-R and Rmax (km) for source-to-site calculations
-17. 22. 0.20   !source region, sampled at 0.2 d increment in lat
88. 117. 0.20   !source region, sampled at 0.2 d increment in long.
1.0 5.0 7.0 0.1 3.0   !default bvalue=1. Mag range 5 to 7, by 0.1
1 0 0   0   !use grid of avalue(rates) but default b, Mmax
d1.a   !name of binary agrid file, output of agrid pgm
1. 0   !cyr, incr=0. If incr=1, convert cumulative to incremental
meanrjb.bin   !this line is used in hazgridXnga4 and hazgridXnga5
4   ! How many spectral periods in analysis?
0.2 0. 0.   !first period, here 0.2 sec SA. Next line: Output file name.
SEasiagrid.5hz
19   !number of ground motions, then list of sampled g.m.
.005 .0075 .0113 .0169 .0253 .0380 .0570 .0854 .128 .192 .288 .432
.649 .973 1.46 2.19 3.28 4.92 7.38

```
2        !number of attenuation models to consider for this period
6 0.5 1000. 0.25 0       !Code 6 is Frankel et al. model. Weigh 0.5
10 0.5 1000 0.5 0        !Code 10 is Campbell&Bozorgnia, highQ
0.3 0. 0.    ! next period: 0.3 sec SA
SEasiagrid.3hz
20              !how many ground motions and list of g.m.
.0025 .00375 .00563 .00844 .0127 .0190 .0285 .0427 .0641 .0961
.144 .216 .324 .487 .730 1.09 1.64 2.46 3.69 5.54
2               !number of attenuation models to use for this period
6 0.5 1000. 0.25 0       !6 is Frankel et al. high-Q model
10 0.5 1000 0.5 0        !Campbell&Bozorgnia CEUS model, hybrid
0.0 0. 0.               !3rd period: PGA=0.0 sec SA
SEasiagrid.pga          !output file name
20
.001 .00375 .00563 .00844 .0127 .0190 .0285 .0427 .0641 .0961
.144 .216 .324 .487 .730 1.09 1.64 2.46 3.69 5.54
2
6 0.5 1000. 0.25 0       !Frankel et al.
10 0.5 1000 0.5 0        !Campbell&Bozorgnia, hybrid
1.0 0. 0.               !4th spectral period: 1.0 sec SA
SEasiagrid.1hz
20
.0025 .00375 .00563 .00844 .0127 .0190 .0285 .0427 .0641 .0961
.144 .216 .324 .487 .730 1.09 1.64 2.46 3.69 5.54
2
6 0.5 1000. 0.25 0       !Frankel et al.
10 0.5 1000 0.5 0        !Campbell&Bozorgnia, hybrid
```

Notes:
(1) The last integer in the two lines immediately above is a zero (0). This is the value assigned to an array element, iconv ( ). Iconv is generally used to convert magnitudes from one form to another. For example, if the input magnitude is mb and the output is Mw, iconv( ) may be used to convert mb to Mw. This use of iconv( ) assumes that the attenuation subroutine coefficients are written with the assumption that the magnitude of interest is Mw (moment magnitude). A second use of iconv( ) is to choose coefficients for the ground-motion prediction. Some attenuation models have two sets of coefficients, one corresponding to mb and another to Mw. For those

cases, iconv( ) is used to select the appropriate set. An example subroutine that uses iconv( ) in this latter sense is "getToro." Iconv( ) is generally used with non-zero values in stable continental regions because earthquake catalogs in those regions are often given with magnitude units mb, mb(Lg) or similar.

(2) If you want to perform analysis for a list of sites instead of a grid of stations, the first line should begin with 1,2,…, or n, then list the station coordinates and their names. Example with n=2:

2
13.65 100.7 Bangkok1
13.75 100.6 Bangkok2
…
In this example, PSHA analysis will be done for two sites in and around Bangkok.

There are many options the code is able to work with. You can use up to seven attenuation models per spectral period. The index or code for each of these is contained in the comments early in the source code.

You can consider up to seven spectral periods per run. Different attenuation models work with different sets of periods of spectral acceleration (SA). If you select commonly considered spectral periods, such as 0.2 and 1.0 s, all of the models will work. If you select some periods, such as 5.0 seconds, many models won't work. Newer models, such as NGA (Next Generation of Attenuation Models) often have more periods to choose from than older models. NGA relations are also capable of predicting motion out to longer periods (5 or even 10 s) than older relations. Long-period analysis is helpful for tall-building hazard and loss studies, as well as long structures such as pipelines and large bridges.

Some relations work with a fixed set of site conditions and some with Vs-30 dependent site conditions. CEUS fixed site is hard rock (HR) or firm rock (FR or BC); WUS fixed site condition is FR or soil. NGA models have continuous variation of site response with Vs30, and have nonlinear soil response. BC is an abbreviation for rock at the NEHRP B/C boundary, Vs30 = 760 m/s. This is the standard site condition adopted by the USGS National Seismic Hazard Mapping Project. Generally CEUS attenuation models are logical choices for use with crustal earthquakes in any of the world's stable cratons, and WUS models are

logical choices for use near active tectonic plate margins. Subduction is another issue, dealt with using different programs and attenuation models.
Here is a current list of attenuation models available in hazgridXnga2:

INDEX   Whose Model? The below indexes are correct through hazgridXnga4. However, there are several additions and a change in hazgridXnga5.

1   Spudich *et al.,* 2000. Model form is based on BJF93. Has siteamp from BJF97.
2   Toro et al., ceus BC rock (this is a high-Q model)
-2   Toro et al., ceus hard rock
3   Sadigh et al (rock-site coeffs.& eqn) firm rock
-3   Sadigh et al (soils-site coeffs.&eqn) in prep aug06 (don't use)
4   AB06 BC Atkinson and Boore 2006 (see Dec. 2006 BSSA, June 2007 erratum)
-4   AB06 hardrock. There is a siteamp that is added to hardrock median;
                however, it is 0 (in logspace) for vs30=760.
5   AB94 ceus for BC rock site condition
-5   AB94 HRceus
6   Frankel et al., BC rock, ceus
-6   Frankel et al., Hard Rock ceus
7   Somerville ceus. BCrock. Note: Somerville is used
                for the finite-fault portion of gridded hazard. Used with Charleston
-7   Somerville ceus. hardrock.
8   Abrahamson-Silva 1997. rock. july 25 2006
9   Campbell and Bozorgnia 2003. rock. july 25 2006
-9   Campbell and Bozorgnia 2003. D soil. future 2006
10   Campbell CEUS BC or firmrock 2003. july 25 2006
-10   Campbell CEUS A or hardrock 2003. aug 2006
11   BJF 1997. All Vs30 allowed, like NGA relations. Mech dependent
12   AB intraslab seismicity Puget Sound region BC-rock condition
-12   AB intraslab seismicity Puget Sound region D-soil condition
13   Geomatrix slab seismicity rock, 1997 srl. july 25 2006
-13   Geomatrix slab seismicity soil, 1997 srl. july 25 2006
14   Motazetti and Atkinson ready for 4 Pds, Has siteamp from BJF97.
15   not currently used (Silva CEUS hazgridXnga4).
18   AB 2003 intraslab seismicity world data BC-rock condition
-18   AB 2003 intraslab seismicity world data region D-soil condition
19   Tabakoli and Pezeshk 2005 added nov 14 2006.
21   Boore-Atkinson nga updated to the Feb 2007 version, with 21 periods.
22   Campbell-Bozorgnia nga updated to the 11-2006 vers, nov 14 2006.
                the CB update includes peak displacement, or **PHD**. Sigma for
                random horizontal component is the default now.
23   Chiou-Youngs nga vers 6-2006. 105 spectral periods

24   Abrahamson-Silva partially set up mar 06 (this relation will probably change).
25   Idriss **PGA only** Oct 2005.
26   Kanno et al. BSSA June 2006. This model has large aleatory sigma for all spectral periods, about 50% larger than NGA relations above.

Changes and additions to above in hazgridXnga5:
14   now is Youngs et al. or Geomatrix with subduction source (as distinct from inslab, index 13).
15   Silva CEUS model
16   AB03 subduction, Cascadia coefficients (as distinct from inslab, index 12)

17   AB03 subduction, Global coefficients (as distinct from inslab, index 18)
27   Zhao et al. (2006) inslab
28   Zhao et al. (2006) subduction
29   Motazetti and Atkinson ready for 4 Pds, Has siteamp from BJF97.

The log file

This file logs or reports many of the input/output activities of the program, and is a guide to what might otherwise be a black-box experience.

This file should be looked at to see if everything worked as you expected it to work. The log file will tell you if certain input parameters were not accepted (out of expected range, needed input file not in the right location, attenuation model index not valid, and many other things). Perhaps certain input values were accepted but a caution message was raised. The log file tells you what attenuation models you are using. Are these the ones that you had intended to use for your ground-motion predictions?

Studying the log file contents is not a sufficient check, however. Examination of the output hazard curves and their relation to the input seismic hazard model are always necessary steps in the validation of the PSHA.

The next pages are an example log file from a run of hazgridXnga2.f.
```
hazgridXnga2 log file. Pgm run on 20070613 at 114648.282 -0600
# Control file:SEasia.shallow.lowQ.in
Enter a zero for grid of sites 1 to 30 for list: 0
 Receiver latitude range  0.0E+0 22.0 0.1
   & Longitude range  94.0 105.0 0.1
 111 221  old calc:  111 221
 Grid_of_sites hazcurves underway
 Softrock has Vs<2500 m/s in below question
 For sites, enter Vs30(m/s) and softrock max depth(km)
 760.0 1.0
 Separate weights for dtor | M<6.5 or M>=6.5 in below question
 Enter ndtor, (dtor(k),wt_65-(k),wt_65+),k=1,..ndtor<=3
 1 5.0 0.0E+0 0.0E+0  km was input
 Enter three weights corresponding to fraction ss, reverse, normal:
 Weights to ss, rev, normal are  0.5 0.0E+0 0.5
```

```
dist incr  1.0  max dist  200.0
Source box xmin,ymin  88.0 -17.0
Magmin,magmax  5.0 7.0
Constant b-value used  1.0  const. mmax  7.0
agrid file ../SEAsia/d1.a

28616 28616  agrid counts
xmagmin and its index for finite fault calcs  6.05 10
6.05 6.9500002 0.1 200.0 0.1 0.1 0 -17.0 22 22.0
NR lat indexes, NL long indexes  39 20  at lat  0.0E+0
NR lat indexes, NL long indexes  39 20  at lat  1.0
NR lat indexes, NL long indexes  39 20  at lat  2.0
NR lat indexes, NL long indexes  39 20  at lat  3.0
NR lat indexes, NL long indexes  39 20  at lat  4.0
NR lat indexes, NL long indexes  39 20  at lat  5.0
NR lat indexes, NL long indexes  39 20  at lat  6.0
NR lat indexes, NL long indexes  39 20  at lat  7.0
NR lat indexes, NL long indexes  39 20  at lat  8.0
NR lat indexes, NL long indexes  39 20  at lat  9.0
NR lat indexes, NL long indexes  39 20  at lat  10.0
NR lat indexes, NL long indexes  39 20  at lat  11.0
NR lat indexes, NL long indexes  39 20  at lat  12.0
NR lat indexes, NL long indexes  39 20  at lat  13.0
NR lat indexes, NL long indexes  39 20  at lat  14.0
NR lat indexes, NL long indexes  39 20  at lat  15.0
NR lat indexes, NL long indexes  39 20  at lat  16.0
NR lat indexes, NL long indexes  39 20  at lat  17.0
NR lat indexes, NL long indexes  39 20  at lat  18.0
NR lat indexes, NL long indexes  39 21  at lat  19.0
NR lat indexes, NL long indexes  39 21  at lat  20.0
NR lat indexes, NL long indexes  39 21  at lat  21.0
NR lat indexes, NL long indexes  39 21  at lat  22.0
mean rjb precalc completed for random-strike flt
0.350517  sec to complete this precalc
Number of spectral periods  4
Output file name for spectral period  0.0E+0 SEasiagrid.lowQ.pga

6 SEasiagrid.lowQ.pga
Number of PGA levels  19
Min/max gm levels  5.0E-3 2.13
Number of attenuation relations is  3
Attenuation index and wt  21 0.334
Attenuation index and wt  22 0.333
Attenuation index and wt  23 0.333
Output file name for spectral period  0.2 SEasiagrid.lowQ.5hz

7 SEasiagrid.lowQ.5hz
Number of pSA levels  19
Min/max gm levels  5.0E-3 7.38
Number of attenuation relations is  3
Attenuation index and wt  21 0.334
Attenuation index and wt  22 0.333
Attenuation index and wt  23 0.333
Output file name for spectral period  0.3 SEasiagrid.lowQ.3hz

8 SEasiagrid.lowQ.3hz
Number of pSA levels  20
```

```
Min/max gm levels  2.5E-3 5.54
Number of attenuation relations is  3
Attenuation index and wt  21 0.334
Attenuation index and wt  22 0.333
Attenuation index and wt  23 0.333
Output file name for spectral period  1.0 SEasiagrid.lowQ.1hz

9 SEasiagrid.lowQ.1hz
Number of pSA levels  20
Min/max gm levels  2.5E-3 5.54
Number of attenuation relations is  3
Attenuation index and wt  21 0.334
Attenuation index and wt  22 0.333
Attenuation index and wt  23 0.333
1000 4.184985E-3 0.0E+0
1000 7.609411E-3 0.2
1000 8.606639E-3 0.3
1000 6.53987E-4 1.0
…
24000 6.1532733E-3 0.0E+0
24000 0.011199041 0.2
24000 0.012906573 0.3
24000 9.739611E-4 1.0
24531 7.634113E-6 0.0E+0
24531 2.8069266E-5 0.2
24531 4.960084E-5 0.3
24531 1.5468139E-6 1.0
 93.796424  sec= time to complete hazgridXnga2
```

The log file echoes much of the input-file information. The fact that this information corresponds to the running commentary, for example, Vs30 = 760 m/s, is a sign that the program has read in the input data in the correct order and is processing it as expected. The line early in the above file about "fraction of ss, rev, normal" asks the user to specify the ratio of strike-slip, reverse-slip, and normal-slip seismicity in the region. These fractions should add to one and reverse slip should not be mixed with normal slip. The NGA relations are sensitive to the style of slip with higher expected motion at sites directly on top of normal- or reverse-slip faults than sites over strike-slip faults. If you are not too sure about the relative frequency of strike-slip and normal-slip activity in the region of interest, you should ask a seismologist.

The "agrid counts" are the number of source cells where earthquake rate information exists. The two numbers are the number that was expected and the number that was actually read in. These should be equal. If they are not equal, the program will issue an error message.

The last several lines of the above log file give you some sample output information at every 1000th station. One piece of output information is given for each input spectral period, here 0 s (PGA), 0.2 s SA, 0.3-s SA, and 1.0-s SA. This piece of information happens to be the mean rate of exceedance of the 9th or 10th sampled ground motion for each spectral period. These rates should be scanned for reasonableness. Most of this information has been omitted for conciseness (omissions are in the … area).

The last line above is the computer run time for the analysis. Here, the time was 94 seconds, or about 1 ½ minutes. Gridded hazard runs typically finish pretty fast, but performance varies depending on the computer and the details of the analysis.

Late Discovery: When running hazgridXnga2 on PCs with Windows operating system, rather than Linux, we find that the gfortran compiler can have difficulties with the erf( ) call inside a subroutine. This call works ok from main, however. Code has been partially modified to avoid the erf() call inside most subroutines. However, erf() is still called from some CEUS attenuation model subroutines, such as getFEA. These calls probably will not work in a PC environment without further software engineering. Steve Harmsen, June 27, 2007.

HazFXnga7c.f

The second main code used in USGS psha analysis was written to determine hazard associated with known faults, that is, faults whose locations have been mapped. There can be uncertainty on the fault location, such as endpoints and fault dip, but any given scenario event has a fixed location. In its current form, this program will compute hazard for up to 500 scenario faults in a given run. The fault information, which should have been output by a program like *fltrate.v2.f*, is listed sequentially. The program reads in a variable number of fault data and proceeds with the analysis when it finds an end-of-information mark in the file or when it reaches the limit of 500. Its log file tells you how many distinct faults or fault scenarios it found. If the number is 500, the log file warns you that additional data may have been omitted.

There are two broad categories of fault hazard: characteristic and Gutenberg Richter (GR). These can be mixed in an input file, but they cannot be mixed in a scenario event. Characteristic events have an index 1 and GR events have index 2. The below sample input file contained in the hazFXnga7c user manual has a characteristic event description.

Scenario events can be sequentially listed for any given fault. These alternative scenarios typically sample uncertainty in event recurrence time or magnitude. Up to 12 scenario events may be listed per fault, each with its weight. These weights are relative to all sources in the input file. In the below sample input file, there is only one scenario event listed.

HazFXnga7c has some special features which distinguish it from many of the predecessor programs in the hazFX family. These are summarized in the following bullets:
- Epistemic branching on median SA, used with NGA equations, selected by making the "wind" variable greater than zero. Wind can differ from spectral period to spectral period for this case only.
- Clustered-event hazard with grouped sources, selected by making the wind variable less than zero, with amplitude equal to the number of groups. This option is discussed in detail in Appendix A. If wind<0, wind should be same for all spectral periods.

- Event-rate bookkeeping, selected by specifying as the 2nd argument, the polygon within which sources will be counted. One or more points on the surface defining the fault must intersect the polygon for the event to be included. This option will only be invoked if you ask for a *list* of sources (usually 1), not for a *grid* of sources.
- Improved fault-to-station distance calculation. The routine mindist1 finds the two main distances used by attenuation models, called Rjb and Rcd, respectively.
- Variable Vs30.

This last new feature allows the analyst to input a grid of Vs30 values. The code finds the location in the Vs30 grid that is closest to the site that is currently being analysed, and uses the Vs30 from that location for the geotechnical site-factor calculations. If the site is outside the Vs30 grid region, a default Vs30 is used. This new feature allows the user to perform a site-specific analysis on a large grid of sites, if the needed Vs30 array is available. This feature was designed to help in the analysis of seismic response in large sedimentary basins with urban populations, but has not yet been used, and would probably benefit from more testing. To invoke the variable Vs30 option, make Vs30 in the below input file zero, and follow that line with 4 lines containing: (1) file name for Vs30 binary array, (2) ymin, ymax, dy for Vs30 array, (3) xmin, xmax, dx for Vs30 array, (4) Vs30 default for sites exterior to the Vs30-defined region.

PSHA Software Documentation

Program: hazFXnga7c.f
Language: fortran95 (gfortran)
Purpose: Compute probabilistic seismic hazard at various sites from a set of known faults
Current Technical Contact: Stephen Harmsen, harmsen@usgs.gov
Date of last Modification: June 10, 2007

To run: hazFXnga7c.exe input.file > log.file
Sample Input File. Comments are given in blue. These blue comments are not read by the program. The data on the left side are what the program needs.
Here is an example input file:

0   !use grid-of-sites option (1 or more implies list of stations)
0 22. 0.1   !min lat, max lat, dlat. Site grid in Thailand&Indonesia
94. 105. 0.1   !min long, max long, dlong (in degrees)
760. 1   !Vs in upper 30 m, 760 m/s here; depth to Vs2500 (km)
1. 200.   !deltaR (km) and Rmax (km). For this run Rmax is 200.
3   !number of spectral periods to consider.
0. 0 0   !0 indicates PGA, 2nd number (0) is "wind"
thaipga.char.highQ   ! output file name
19   ! number of PGA samples. Next lines are sample values
.005 .007 .0098 .0137 .0192 .0269 .0376 .0527 .0738 .103 .145 .203
.284 .397 .556 .778 1.09 1.52 2.13
2   !number of attenuation models to use in analysis
2 0.5 1000. 1 0 !Toro model at NEHRP B/C boundary, half weight
7 0.5 1000. 1 0 !Somerville *et al.* for finite faults, half weight
0.2 0 0   !0.2-sec PSA (5 hz), Second number (0) is "wind"
thai5hz.char.highQ   ! output file name
19
.005 .0075 .0113 .0169 .0253 .0380 .0570 .0854 .128 .192 .288 .432
.649 .973 1.46 2.19 3.28 4.92 7.38
2
2 0.5 1000. 1 0 !Toro NEHRP B/C atten
7 0.5 1000. 1 0 !Somerville finite faults
1.0 0 0 sec PSA !1-s is 3rd spectral period. Second number is "wind"
thai1hz.char.highQ   ! output file name
20   !number of 1-s SA samples is 20. Here they are:
.0025 .00375 .00563 .00844 .0127 .0190 .0285 .0427 .0641 .0961
0.144 .216 .324 .487 .730 1.09 1.64 2.46 3.69 5.54

```
2                       !number of attenuation models for 1-s
2 0.5 1000. 1 0 !Toro NEHRP B/C site. Half weight to 1000 km.
7 0.5 1000. 1 0 !Somerville finite faults, half weight to 1000 km.
1. 1.                   !distance sampling on fault (km) and dmove (km)
1                       !number of epistemic branches on magnitude, 1
0                       !dM for branches (0 here because only one)
1                       !weights for branches (full weight for only branch)
0 1                     !dM for aleatory branches (also 0 here). Mwid.
 1 3 1    ! Thoen fault , 1= characteristic, 3=normal slip 1= # of Mags
 7.43 2.450473E-4 1.0 !Char. mag, char rate, epistemic weight (1)
 60.0 17.320515 0.0E+0 106.646514      !dip(d), fault width, top(km)
 9                      !number of points on discretized fault
    18.26392       99.81272   !lat°, long° of 1st point of Thoen fault
    18.17707       99.74847   !lat, long of 2nd point
    18.10844       99.69968   !Other points follow
    18.04114       99.58109
    18.01505       99.57042
    17.93080       99.45937
    17.78529       99.35471
    17.66522       99.30668
    17.52629       99.20238
…                                !Continue listing fault descriptions here.
(The above fault was computed to be 106.64 km long.)
```

Notes: If you want to perform analysis for a list of sites instead of a grid of stations, the first line of file should begin with n, the number of stations (<30). Then list the station coordinates and their names. Example:

```
2
13.65 100.7 Bangkok1
13.75 100.6 Bangkok2
…
```

In this example, PSHA analysis will be done for two sites in and around Bangkok.

There are many options the code is able to work with. You can use up to seven attenuation models per spectral period. The index or code for each of these is contained in the comments early in the source code.

You can consider up to seven spectral periods per run. Different attenuation models work with different sets of periods. If you select common periods, such as 0.2 and 1.0 s, all of the models will work. If you select uncommon periods, such as 5.0 seconds, many models won't work. Newer models, such as NGA (Next Generation of Attenuation Models) often have more periods to choose from. Attenuation model Indexes are similar to those of hazgridXnga2 but they can be different.
Here is a current list of attenuation models available in hazFXnga7:

Some are for fixed site conditions and some for
Vs-30 dependent site conditions. CEUS fixed site is HR or FR; WUS FR or soil.

INDEX	Whose Model?
1	Spudich *et al.*, 2000. Model form is based on BJF93. Has BJF97 siteamp
2	Toro *et al.* (SRL, 1997) ceus BC rock (this is a high-Q model)
-2	Toro *et al.* ceus hard rock
3	Sadigh *et al.* (rock-site coeffs.& eqn) firm rock
4	AB06 BC Atkinson and B00re 2006
-4	AB06 hardrock. There is a siteamp that is added to hardrock median; however, it is 0 (in logspace) for vs30=760.
5	AB94 ceus for BC rock site condition
-5	AB94 HRceus
6	Frankel *et al.* BC rock, ceus
-6	Frankel *et al.* HardRock ceus
7	Somerville *et al.* ceus. BCrock. Use with faults in high-Q environment
-7	Somerville ceus. hardrock.
8	Abrahamson-Silva 1997. firm rock.
9	Campbell and Bozorgnia 2003. firm rock.
10	Campbell CEUS BC or firmrock 2003.
-10	Campbell CEUS NEHRP A or hardrock 2003.
11	BJF 1997. All Vs30 allowed, like NGA relations. Mech dependent
12	Motazetti and Atkinson, developed for Puerto Rico/VI. Limited period set.
13	boore-atkinson nga updated to the 10-27-2006 version
14	campbell-bozorgnia nga updated to the 11-2006 version the CB update includes peak displacement, a novelty. Sigma for random horizontal component is the default now.
15	chiou-youngs nga version 6-2006. Has 105 spectral periods, no PGV.
16	abrahamson-silva preliminary nga. Do not use. This will change.
17	Idriss NGA model. For pga only, oct 2005.

The log file

This file logs or reports many of the input/output activities of the program, and is a guide to what might otherwise be a black-box experience.

This file should be looked at to see if everything worked as you expected it to work. The log file will tell you if certain input parameters were not accepted (out of expected range, needed input file not in the right location, attenuation model index not valid, and many other things). Perhaps certain input values were accepted but a caution message was raised.

Examining the log file should help the user to debug the input file. Studying the log file contents is not a sufficient check, however. Examination of the output hazard curves and their relation to the input seismic hazard model are always necessary steps in the validation of the PSHA.

The next lines are an example log file from a run of hazFXnga7c.f:

```
# *** hazFXnga7c log file. Pgm run on 20070607 at 153536.264
# *** Input control file: thai.new.gr
For sites: enter min lat, max lat, dlat: 0.0E+0 22.0 0.1
for sites: enter min lon, max lon, dlon: 94.0 105.0 0.1
 111 221  nx ny for discrete grid of sites
  Vs30 and depth of basin  760.0 3.0
 Distance increment and dmax  1.0 200.0
 Period  0.0E+0  underway
 5 thaipga.gr.lowQ
 Nlev  19  min max  5.0E-3 2.13
 number of atten. relations for this period  3
B&A 02/07NGA attenuation model assoc. with index 1
 1 21 BA 2/2007 ip map
C&B11/06 NGA attenuation model assoc. with index 2
 1 1  campbell 10/06 ip map
Chiou-Y 9/06 attenuation model assoc. with index 3
 1 1  CY 9/06 ip map
 Period  0.2  underway
 6 thai5hz.gr.lowQ
 Nlev  19  min max  5.0E-3 7.38
 number of atten. relations for this period  3
B&A 02/07NGA attenuation model assoc. with index 1
 2 10  BA 2/2007 ip map
C&B11/06 NGA attenuation model assoc. with index 2
 2 8  campbell 10/06 ip map
Chiou-Y 9/06 attenuation model assoc. with index 3
 2 38  CY 9/06 ip map
 Period  1.0  underway
 7 thai1hz.gr.lowQ
 Nlev  20  min max  2.5E-3 5.54
 number of atten. relations for this period  3
B&A 02/07NGA attenuation model assoc. with index 1
 3 16  BA 2/2007 ip map
C&B11/06 NGA attenuation model assoc. with index 2
 3 14  campbell 10/06 ip map
Chiou-Y 9/06 attenuation model assoc. with index 3
 3 68  CY 9/06 ip map
```

```
dlen, dmove (km)= 1.0 1.0
Number of epistemic M-branches:  1
epistemic dM=  0.0E+0 0.0E+0 0.0E+0
0.0E+0  sd_aleatory
1
2 3 1 1    1,Thoen fault
Zeng algorithm for floating ruptures w/variable dip direction
***********************#####*********************************
a b magmin magmax relwt 3.234987 1.0 6.5 7.43 1.0
4.906856E+16
xmag, rate  7.371875 3.234987 3.234987
Dip width depth0  50.0 19.58112 0.0E+0
9 106.64582
107 3 -141.6885
Resampling at  1.0  km for fault number  1 107
2
2 3 1 1    2,Long fault
Zeng algorithm for floating ruptures w/variable dip direction
***********************#####*********************************
a b magmin magmax relwt 2.4293975 1.0 6.5 7.17 1.0
4.8469022E+15
xmag, rate  7.1141667 2.4293975 2.4293975
Dip width depth0  50.0 19.58112 0.0E+0
6 63.206214
64 3 48.50206
Resampling at  1.0  km for fault number  2 64
3
2 3 1 1    3,Phrae fault
Zeng algorithm for floating ruptures w/variable dip direction
***********************#####*********************************
a b magmin magmax relwt 2.3479063 1.0 6.5 7.24 1.0
5.608501E+15
xmag, rate  7.1937494 2.347906 2.3479063
Dip width depth0  50.0 19.58112 0.0E+0
7 73.1386
74 3 13.851041
Resampling at  1.0  km for fault number  3 74
4
2 3 1 1    4,Phrae Basin fault
Zeng algorithm for floating ruptures w/variable dip direction
***********************#####*********************************
a b magmin magmax relwt 2.4354002 1.0 6.5 7.18 1.0
4.9462765E+15
xmag, rate  7.1233334 2.4354002 2.4354002
Dip width depth0  50.0 19.58112 0.0E+0
6 64.501625
65 3 -151.93546
Resampling at  1.0  km for fault number  4 65
5
2 3 1 1    6,Nam Pat fault
Zeng algorithm for floating ruptures w/variable dip direction
***********************#####*********************************
a b magmin magmax relwt 2.4551472 1.0 6.5 6.91 1.0
2.9072335E+15
xmag, rate  6.85875 2.4551472 2.4551472
Dip width depth0  50.0 19.58112 0.0E+0
6 37.91209
```

```
38 3 29.021194
Resampling at  1.0   km for fault number  5 38
6
2 3 1 1    7,Pua fault
Zeng algorithm for floating ruptures w/variable dip direction
*************************####*********************************
a b magmin magmax relwt 3.151146 1.0 6.5 7.29 1.0
3.684425E+16
xmag, rate  7.240625 3.151146 3.151146
Dip width depth0  50.0 19.58112 0.0E+0
14 80.07862
81 3 173.14755
Resampling at  1.0   km for fault number  6 81
7
2 3 1 1    8,Phayao fault
Zeng algorithm for floating ruptures w/variable dip direction
************************####**********************************
a b magmin magmax relwt 2.3873713 1.0 6.5 6.8 1.0
2.3251602E+15
xmag, rate  6.7625 2.387371 2.3873713
Dip width depth0  50.0 19.58112 0.0E+0
5 30.32111
31 3 -16.138138
Resampling at  1.0   km for fault number  7 31
8
2 1 1 1    9,Mae Chan fault
Zeng algorithm for floating ruptures w/variable dip direction
************************####**********************************
a b magmin magmax relwt 3.4424848 1.0 6.5 7.62 1.0
9.011274E+16
xmag, rate  7.55 3.442485 3.4424848
Dip width depth0  90.0 15.0 0.0E+0
9 154.03908
155 3 69.28581
Resampling at  1.0   km for fault number  8 155
9
2 1 1 1    10,Sagaing fault zone,shortened N
Zeng algorithm for floating ruptures w/variable dip direction
************************####**********************************
a b magmin magmax relwt 5.138578 1.0 6.5 8.0 1.0
5.8683013E+18
xmag, rate  7.90625 5.1385793 5.138578
Dip width depth0  90.0 15.0 0.0E+0
6 724.47735
725 3 175.12367
Resampling at  1.0   km for fault number  9 725
10
2 1 1 1    11,Three Pagodas fault
Zeng algorithm for floating ruptures w/variable dip direction
************************####**********************************
a b magmin magmax relwt 3.6817955 1.0 6.5 8.0 1.0
2.0498831E+17
xmag, rate  7.90625 3.681796 3.6817955
Dip width depth0  90.0 15.0 0.0E+0
13 379.60693
380 3 139.99269
Resampling at  1.0   km for fault number  10 380
```

```
11
2 1 1 1     12,Mae Kuang fault
Zeng algorithm for floating ruptures w/variable dip direction
*************************#####*******************************
a b magmin magmax relwt 2.8241577 1.0 6.5 6.86 1.0
6.5936794E+15
xmag, rate  6.815 2.8241577 2.8241577
Dip width depth0  90.0 15.0 0.0E+0
3 34.075973
35 3 57.300601
Resampling at  1.0  km for fault number  11 35
12
# nft= 11
Fault points w/resampled coords in resample.fault
1000 1.0E-21
2000 1.0E-21
3000 1.0E-21
…
24531 1.0E-21
2231.9724  s = time to complete hazFXnga7c
```

This log file echoes much of the input file information. The fact that this information corresponds to the running commentary, for example, Vs30 = 760 m/s, is a sign that the program has read in the input data in the correct order and is processing it as expected. The last line gives you the amount of time the computer spent on this file. In this case, the run took over 2200 seconds (37+ minutes) to complete the analysis. Different computers' performance will vary.

Subduction hazard: HazSUBXnga

Hazard from the subducting slab is computed using the program hazSUBXnga.f. This code uses a different source-to-site distance algorithm from that of hazFXnga7c. For consistency with previous USGS PSHA models we have retained the distance algorithm used by the earlier members of the hazSUBX family of programs. Much of the hazFX terminology is retained in the hazSUBX family. In particular hazSUBXnga recognizes type 1 (characteristic) and type 2 (GR) ruptures, just like the hazFX codes.

The set of attenuation models for subduction sources is different from those of crustal sources. The indexes used to invoke the various attenuation models range from 2 to 16. Three new attenuation models are those of Zhao *et al.,* with index 7, Kanno *et al.,* with index 8, and Gregor *et al.*, with index 16. The user is cautioned that these index values may look the same as those of hazFXnga programs, but their meanings are totally different. These indexes are specific to hazSUBXnga, and will not necessarily be the same as those of earlier hazSUBX programs. Some attenuation models have been used for both crustal and interface earthquake sources. These are Kanno *et al.* and Sadigh *et al.*

In the terminology of earthquake seismology, a characteristic event tends to fill the entire fault, or in this case, the subducting slab, with a single event. If the modeled sources fill the available slipped area with a distribution of floating ruptures, the alternate GR rupture style (type 2) is implied. For the case of the Indian Ocean plate subduction, which is

considered in the example input file that follows, the length is much too long for a single characteristic event to fill the entire zone. Thus, floating ruptures, perhaps all with a given magnitude, are used to define the hazard from a subducting slab. In the example input file that follows, the size (**M**) of the characteristic event is 9.2, but this is not large enough to fill the defined subduction zone. The input file defines the **M**9.2 event as a type 2 or GR rupture. Its a-value is 7.2, its b-value is 1.0. Thus, the mean rate of **M**9.2 events in the below example is $10^{7.2-9.2}=10^{-2}=0.01$, for a mean recurrence time of 100 years. The recurrence time for events within a restricted distance range of any given site would tend to be longer than 100 years, because many of the slab sources would be outside this range. Figure 1 illustrates how a floating **M**9.2 event produces lower hazard towards the slab endpoints, greater hazard towards the interior of the slab. For this figure, the easternmost subducting slab edge is located at 112º E. Note that the maximum 1-s spectral acceleration is not attained until several degrees W of this endpoint, at 104º or so.

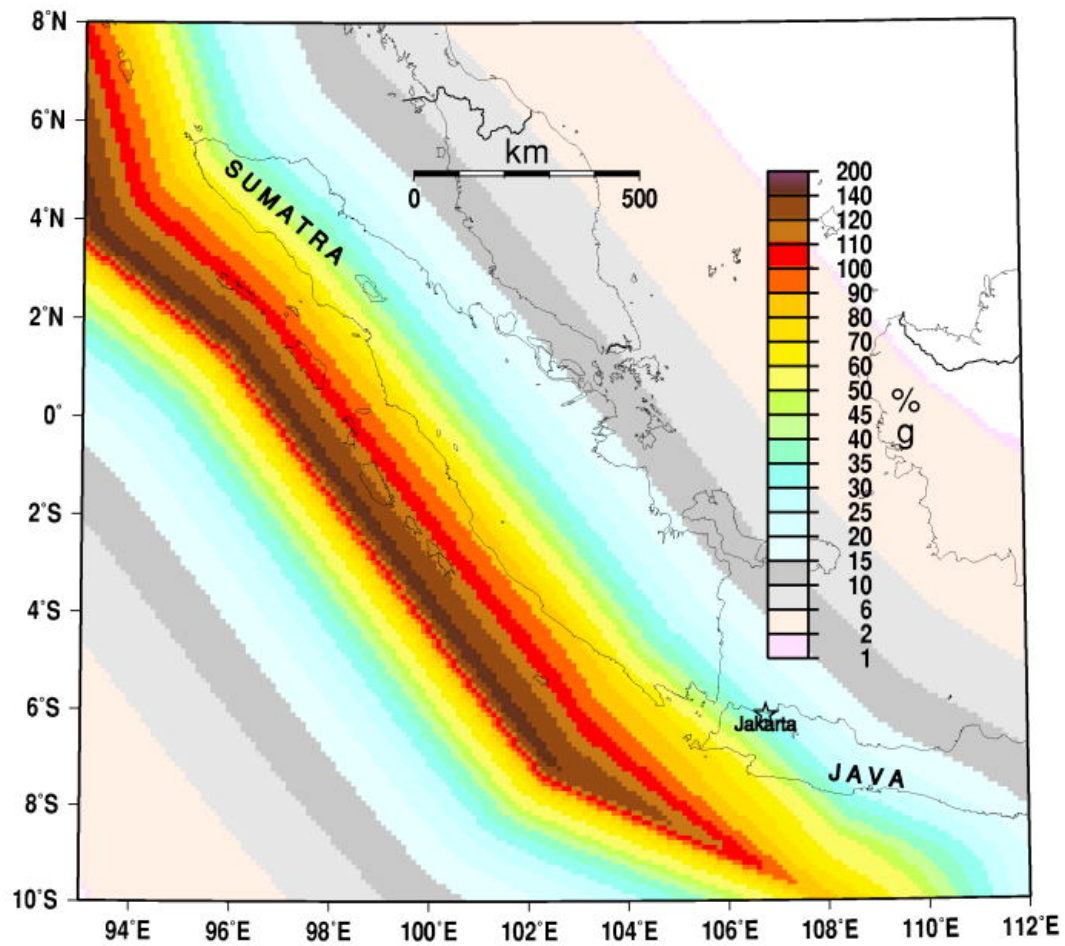PSHA 1hz Indonesia Subduction. PE= 2% 50 yr

Figure 1. 1-Hz seismic hazard associated with a floating **M**9.2 rupture on subducting slab.

HazSUBXnga has the option to read in and use a variable Vs30 array. The way this is done is just like the way it is done in *hazFXnga7c.f*. Please read the discussion of *hazFXnga7c.f* to learn how to work with the variable Vs30 option. Otherwise, just enter

the fixed Vs30 for all sites. Subduction attenuation equations generally do not have a continuously varying Vs30 in their geotechnical model of site amplification, although a few of the most recent ones do. Several models, such as that of Atkinson and Boore, have provisions for site classes, however. The fixed-Vs30 option for BC rock is invoked in the sample input file below. For this case, the code uses an average of the B-class and the C-class to define a median response at the BC boundary.

The user documentation for hazSUBXnga follows.

Program: hazSUBXnga.f
Language: fortran95 (gfortran)
Purpose: Compute probabilistic seismic hazard at various sites from one fault or subducting slab whose top and bottom contours are specified.
Current Technical Contact: Stephen Harmsen, harmsen@usgs.gov
Date of last Modification: May 10, 2007

To run: hazSUBXnga.exe input.file > log.file
Sample Input File. Comments are given in blue. These blue comments are not read by the program. The data on the left side are what the program needs.
Here is an example input file:

0   !use grid-of-sites option (1 or more implies list of stations)
0 22. 0.1   !min lat, max lat, dlat. Site grid in Thailand&Indonesia
94. 105. 0.1   !min long, max long, dlong (in degrees)
760. 1   !Vs in upper 30 m, 760 m/s here; depth to Vs2500 (km)
3   !number of spectral periods. Here, 3.
0.   !first period to consider 0 = PGA. Next line, output file
slab-pga.50z.new
3   ! number of attenuation models for PGA
2 0.25 1000. 0.25 0   ! 2 is index for Geomatrix subduction
5 0.25 1000. 0.25 0   !5 is index for ABSub, global coefficients
7 0.50 1000. .5 0   !7 is index for Zhao et al. (BSSA, 2006)
19   !number of PGA values to sample and list them(g)
.005 .007 .0098 .0137 .0192 .0269 .0376 .0527 .0738 .103 .145 .203
.284 .397 .556 .778 1.09 1.52 2.13
0.2 sec PSA   !2nd period to consider. Here, 0.2-s SA, or 5-Hz
slab-5hz.50z.new
3
2 0.25 1000. 0.25 0   ! 2 is index for Geomatrix subduction
5 0.25 1000. 0.25 0   !5 is index for ABSub, global coefficients
7 0.50 1000. .5 0   !7 is index for Zhao et al. (BSSA, 2006)
19
.005 .0075 .0113 .0169 .0253 .0380 .0570 .0854 .128 .192 .288 .432
.649 .973 1.46 2.19 3.28 4.92 7.38
1.0 sec PSA   !3rd period to analyze

```
slab-1hz.50z.new
3
2 0.25  1000. 0.25 0      ! 2 is index for Geomatrix subduction
5 0.25 1000. 0.25 0      !5 is index for ABSub, global coefficients
7 0.50 1000. .5 0        !7 is index for Zhao et al. (BSSA, 2006)
20                       !number of SA levels for 1s SA
.0025 .00375 .00563 .00844 .0127 .0190 .0285 .0427 .0641 .0961
.144 .216 .324 .487 .730 1.09 1.64 2.46 3.69 5.54
5.                       !distance increment for source segment (km)
1. 1000.                 !dR and Rmax (km) for source-to-site distances
2  2   Sumatra Megathrust
  7.2   1.0   9.2  9.2  0.1!first number is rate of M0, 1 is bvalue, 9.2 M
6    top                 !number of sample points defining top-of-fault
17.42919239 93.68470752   5      !Lat, long°, depth (km) 1st point
13.66770451 92.14833959 5        !Lat, long°, depth (km) 2nd point
10.30064251 91.56807859 5
3.716000503 93.22699759 5
1.4869995 96.0882512 5.0         !Lat, long°, depth (km) 5th point
-7.197000 102.4520036 5.0
6 bottom                 !number of points defining bottom-of-fault
17.094216 94.59746321 50         !Lat, long°, depth (km) 1st point
13.42208668 93.31859165 50
10.43153688 92.89230113 50
4.691394861 94.61522532 50
2.728670788 96.87101265 50.0
-5.594179503 103.4785157 50.0   !Lat, long (°), depth (km) 6th point
```

Notes:
When running hazSUBXnga, only one fault or slab is allowed per run.
The above is a complete file. You cannot add more subduction
sources to this run. Try another run if you have another source.

If you want to perform analysis for a list of sites instead of a grid of
stations, the first line of file should begin with *n*, the number of
stations (<30). Then list the station coordinates and their names.
Example:

```
2
13.65 100.7 Bangkok1
13.75 100.6 Bangkok2
```

…
In this example, PSHA analysis will be done for two sites in and around Bangkok.

There are many options the code is able to work with. You can use up to five attenuation models per spectral period. The index or code for each of these is contained in the comments early in the source code.

You can consider up to seven spectral periods per run. Different attenuation models work with different sets of periods. If you select common periods, such as 0.2 and 1.0 s, all of the models will work. If you select uncommon periods, such as 5.0 seconds, many models won't work. Newer models, such as Gregor(2006) often have more periods to choose from. Attenuation model indexes are different from those of hazgridXnga2 and hazFXnga7.
Here is a current list of attenuation models available in hazSUBnga:

  Some are for fixed site conditions and some for
  Vs-30 dependent site conditions. Please study source code to determine if a given Vs30 is properly modeled.

INDEX   Whose Model?
1   not used in this code
2   Geomatrix subduction (Youngs *et al*, SRL, 1997)
3   Sadigh *et al.* (rock-site coeffs.& eqn) firm rock. Sometimes used for near-source sites
4   AB03 BC rock and Cascadia, Atkinson and B00re (BSSA, Aug. 2003)
5   AB03 BC rock and global source
6   Crouse (this relation is no longer used)
7   Zhao et al., with variable Vs30. (See BSSA, June, 2006)
8   Kanno et al., shallow sources (lumps subduction with all eqs w/ Z<30 km)
15   Gregor *et al.*, BSSA (2002). Out of date version of Gregor, do not use.
16   Gregor *et al.*, SRL (2006). This replaces 15. Variable nonlinear site amplification, continuous function of Vs30.

The log file

This file logs or reports many of the input/output activities of the program, and is a guide to what might otherwise be a black-box experience.

This file should be looked at to see if everything worked as you expected it to work. The log file will tell you if certain input parameters were not accepted (out of expected range, needed input file not in the right location, attenuation model index not valid, and many

other things). Perhaps certain input values were accepted but a caution message was raised.

Examining the log file should help the user to debug the input file. Studying the log file contents is not a sufficient check, however. Examination of the output hazard curves and their relation to the input seismic hazard model are always necessary steps in the validation of the PSHA.

The next lines are an example log file from a run of hazSUBXnga.f.

```
 HazSUBXnga updated April 2007;  input file thai.subd.in
 Date of run 20070607 at 155654.380
Enter a zero for grid of sites 1 to 30 for list: 0
For sites: enter min lat, max lat, dlat: 0.0E+0 22.0 0.1
for sites: enter min lon, max lon, dlon: 94.0 105.0 0.1
 111 221  nx ny for discrete grid of sites
  Vs30 m/s is   760.0
 Number of periods  3
 5 slab-pga.50z.new
Number of atten. relations for this period: 3
Type of atten. relation, weight, mb to M conv. 2 0.25 1000.0 1.0 0
 Period map for Geomatrix  1
Type of atten. relation, weight, mb to M conv. 5 0.25 1000.0 1.0 0
 Atkinson Boore 2003 subduction model
 Using ABsub with global coef, period map is  1
Type of atten. relation, weight, mb to M conv. 7 0.5 1000.0 1.0 0
 Period map for Zhao et al. 1
Number of ground motion levels: 19
 Ground motion levels
 5.0E-3 7.0E-3 9.8E-3 0.0137 0.0192 0.0269 0.0376 0.0527 0.0738 0.103
0.145 0.203
 0.284 0.397 0.556 0.778 1.09 1.52 2.13
 6 slab-5hz.50z.new
Number of atten. relations for this period: 3
Type of atten. relation, weight, mb to M conv. 2 0.25 1000.0 1.0 0
 Period map for Geomatrix  2
Type of atten. relation, weight, mb to M conv. 5 0.25 1000.0 1.0 0
 Atkinson Boore 2003 subduction model
 Using ABsub with global coef, period map is  2
Type of atten. relation, weight, mb to M conv. 7 0.5 1000.0 1.0 0
 Period map for Zhao et al. 5
Number of ground motion levels: 19
 Ground motion levels
 5.0E-3 7.5E-3 0.0113 0.0169 0.0253 0.038 0.057 0.0854 0.128 0.192
0.288 0.432
 0.649 0.973 1.46 2.19 3.28 4.92 7.38
 7 slab-1hz.50z.new
Number of atten. relations for this period: 3
Type of atten. relation, weight, mb to M conv. 2 0.25 1000.0 1.0 0
 Period map for Geomatrix  3
Type of atten. relation, weight, mb to M conv. 5 0.25 1000.0 1.0 0
 Atkinson Boore 2003 subduction model
 Using ABsub with global coef, period map is  3
Type of atten. relation, weight, mb to M conv. 7 0.5 1000.0 1.0 0
 Period map for Zhao et al. 14
```

```
Number of ground motion levels: 20
 Ground motion levels
 2.5E-3 3.75E-3 5.63E-3 8.44E-3 0.0127 0.019 0.0285 0.0427 0.0641
0.0961 0.144
 0.216 0.324 0.487 0.73 1.09 1.64 2.46 3.69 5.54
 Unusual sum of att. model wts for outer annulus  2.0
 period index  1
 Unusual sum of att. model wts for outer annulus  2.0
 period index  2
 Unusual sum of att. model wts for outer annulus  2.0
 period index  3
Increment dlen (km) for source segment 5.0
Distance increment, dmax (km): 1.0 1000.0
 1
Enter 1 for char. 2 for G-R; 1 for SS, 2 for reverse: 2 2
enter a,b,min M,max M,dmag for freq mag curve7.2 1.0 9.2 9.2 0.1
 6
 resample
 6
 resample
 normvec
 3183.5478  total length (km)
 2
Enter 1 for char. 2 for G-R; 1 for SS, 2 for reverse: nft= 1
 Finished writing header period index  1
 Finished writing header period index  2
 Finished writing header period index  3
 nrup(m),ruplen,tlen 406 1160.7756 3183.5478
 Annual Frequency (m)= 0.01
  Mag  9.2  nrup is  406
 250 8.3810556E-4
 500 4.1899504E-4
 750 9.326136E-5
…
 24250 8.149549E-3
 24500 6.6433646E-3
 24531 3.95907E-3
 133.38869  s = time to complete hazSUBXnga
```

This log file echoes much of the input data and gives some selected output information as well. The last line is the computer CPU time to perform the analysis, here 133 seconds, or a little over 2 minutes. Subduction hazard analysis is often fast, especially if only one magnitude is being considered. Here, we know that only one magnitude was considered, because Mmin and Mmax were both 9.2. This is the magnitude of a megathrust event, similar to the December, 2004 Sumatra event. Sometimes we consider alternative models with uncertain magnitude, sometimes ranging from 7.5 to 9.2, with a Gutenberg Richter distribution on magnitude, frequency. These runs take somewhat longer compared to the above megathrust run.

In the above log file, it is stated that the modeled source rupture length is 1160.8 km whereas the subduction zone length is 3184 km. To fill the zone, the code puts in a large number of overlapping "floating" ruptures each of length 1160.8 km. These start at one end of the trench and march along at 5 km increments, until one of them reaches the other

end of the trench. In this instance, the code put in 406 of these floating ruptures. The code has an upper limit on how long this subduction zone can be. You can remove parts of the zone that are not of any significance to your particular hazard analysis to fit the model into the limited array space that was allocated in the software.

Combining hazard curves

During a seismic hazard analysis for a large region, such as a country, there will typically be several separate runs corresponding to different kinds of seismic sources. At some point, the analyst will decide that he/she has defined all of the competent sources. All of his component hazard files must now be combined to produce a set of mean hazard curves, one for each location and for each spectral period. Whether these curves represent independent sources, or the same sources with different parameterizations and associated weights (uncertainties), the mean hazard is computed by adding up all of the weighted hazard curves for competent sources that could affect the sites.

The next figure is a graph which shows an example summation of hazard curves for a site in western Thailand. For this example, seismic hazard at this site is affected by sources contained in six different hazard runs, one for deep gridded, one for shallow gridded, two for GR fault hazard (groups 1 and 2), one for characteristic faults, and one for subduction of the Indian Ocean plate. These are the six colored curves. The weighted sum, that is, the mean hazard, is graphed as the black curve. When hazard maps are made, we use the value at the appropriate ordinate (Y-axis value) from this black curve. The X-axis represents 1-s spectral acceleration in units g (gravity, 980 cm/s^2). For example, if you are interested in the 10^{-3} frequency of exceedance, or 1000-year ground acceleration, it is almost 0.1 g at this site (BC rock site condition).
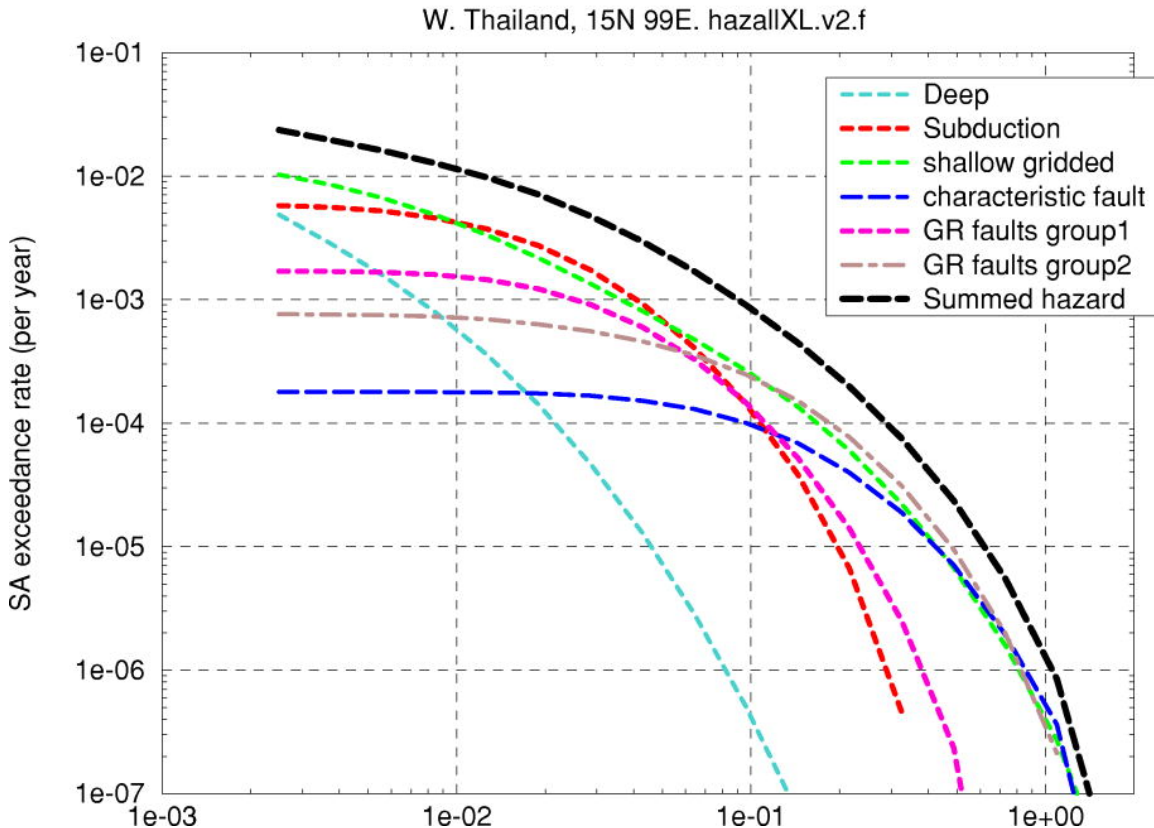

Figure 2. Summing hazard curves. The X axis is 1-s SA (g). Soil condition: BC rock.

The below documentation should help to familiarize you with the hazard code that is used to combine hazard curves from grids of sites and from many files. Two sample input files are discussed. The first input file tells the program to produce one value at each site, where that value is the 1-Hz SA having 2% in 50 year probability of exceedance (or annual rate of 4.04E-4). The second input file tells the program to produce a hazard curve at each site. A hazard curve is a set of sampled ground motions with their associated probabilities (rates) of exceedance.

Program: hazallXL.v2.f
Language: fortran95 (gfortran)
Purpose: Combine probabilistic seismic hazard curves at grid of sites into 1 of two outputs. (1) mapped probabilistic motions at a specified probability of exceedance, or (2) set of total hazard curves for all sites in the grid. Other options are possible but are not discussed.
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To run: hazallXL.v2.exe input.file > log.file

Sample Input File 1. Comments are given in blue. These blue comments are not read by the program. The data on the left side are what the program needs.
Here is an example input file of type 1 above:

```
1                    !new input format, grid of sites
7                    !number of files to combine, 7 here
SEasiadeep.5hz       !first file name (corresponds to deep intraplate eqs)
1                    !weight to apply to first file
slab-5hz.50z.new     !2nd file name (has to do with subduction earthquakes)
1                    !2nd file's weight
SEasiagrid.5hz       !3rd file name (has to do with background seismicity)
1                    !3rd file's weight
thai5hz.char.highQ       !4th file name (has to do with char. faults)
0.67                     !4th file's weight
sumatra5hz.char.lowQ     !5th file name (Sumatra fault hazard)
0.67                     !5th file's weight
thai5hz.gr.highQ         ! 6th file name (has to do with GR faults)
0.33                     ! 6th file's weight
sumatra5hz.gr.lowQ       ! 7th file name (Sumatra fault hazard)
0.33                     ! 7th file's weight
0                        ! output motion at a specific probability level
SEasia.prelim.5hz.2pc50 !output file name
1                        !write file in ascii format (0 if binary)
4.04e-4                  !use this annual rate of exceedance (2%/50 yr)
0                        !0 means output ground motion.
1                        !scale factor, here 1.0 or no scaling.
```

Sample Input File 2. Comments are given in blue. These blue comments are not read by the program. The data on the left side are what the program needs.
Here is an example input file of type 2 above. Note that the first several lines are identical. The first different line is marked in red.

```
1                !new input format, grid of sites
7                !number of files to combine, 7 here
SEasiadeep.5hz    !first file name (corresponds to deep intraplate eqs)
1                !weight to apply to first file
slab-5hz.50z.new  !2nd file name (has to do with subduction earthquakes)
1                !2nd file's weight
SEasiagrid.5hz    !3rd file name (has to do with background seismicity)
1                !3rd file's weight
thai5hz.char.highQ    !4th file name (has to do with char. faults)
0.67                  !4th file's weight
sumatra5hz.char.lowQ  !5th file name (Sumatra fault hazard)
0.67                  !5th file's weight
thai5hz.gr.highQ      ! 6th file name (has to do with GR faults)
0.33                  ! 6th file's weight
sumatra5hz.gr.lowQ    ! 7th file name (Sumatra fault hazard)
0.33                  ! 7th file's weight
1                     ! 1 means output set of hazard curves
SEasia.prelim.5hz.crv ! output file name
0                     !1 means ascii output, 0 for binary output.
1                     !scale factor (not used in this case).
```

This second type of output tends to produce large files, especially if you choose ascii output format. Each site in the grid will have a hazard curve composed of 20 or so points. There can be several thousand sites in a given analysis. Therefore, you should expect the output file to be several megabytes long. Be sure you have adequate space available on your disk if you choose this option.

This program will check for consistency and compatibility of the various input files. If it discovers problems it will try to let you know what went wrong. For example, you must sample the same spectral period in all input files. You must also sample the same set of ground motions. The regions should be the same but the code does try to accommodate some variation in sampled regions if it can.

Where do we go from here?

Once hazard curves for component sources have been combined, typically, the next step is to produce maps. Maps are made of the probabilistic ground motions at various probabilities of exceedance (PE) that have been agreed upon as important by the seismologists, engineers, and building community at large. In the U.S.A., the PEs of most common interest are 2% in 50 years, 5% in 50 years, and 10% in 50 years. Some applications are also interested in the 20% PE in 75 years, and so on. Critical nuclear facility seismic hazard analysis often requires determination of probabilistic ground motion with a low PE, such as 10^{-4} and 10^{-5}. The Generic Mapping Tool (GMT) software

package of Wessel and Smith has been helpful to USGS for producing seismic hazard maps. Figure 1 above was made with GMT, for example.

Often, the initial PSHA is performed for a specific site condition such as rock at the NEHRP BC boundary (760 m/s Vs30). Then, subsequent PSHA is performed for other site conditions, such as NEHRP C-soil, NEHRP D-soil, and NEHRP A- or B- rock. Soil PSHA is important because buildings, pipelines, etc., are frequently built in sedimentary basins. The core hazard codes can work with variable Vs30, but there is a demand for a set of fixed Vs30 hazard maps. Keeping Vs30 variability a separate issue from seismic hazard maps helps engineers understand how Vs30 relates to all other seismic hazard factors and uncertainties.

Two other major avenues for continued analysis are logic tree analysis and seismic source deaggregation. Logic tree analysis computes not just the mean hazard, but also the set of fractile curves from alternate models of source and attenuation. This kind of analysis provides some idea of the uncertainty of the mean among other things. Often the range of hazard curves between the 15% curve and the 85% curve is considered a reasonable estimate for the uncertainty of the mean.

Deaggregation analysis produces reports on the hazardous sources, the relative contribution of binned magnitude and distance, and other details, that help engineers select time histories that correspond to the most likely scenario events to produce a ground motion at or perhaps exceeding some agreed-upon level, say the 2% in 50 year SA.

USGS has many codes to perform the above additional analysis. We are revising these at the time of this writing (June, 2007) to work with all of the new developments that have been included in the core hazard codes, hazgridXnga2, hazFXnga7c, and hazSUBXnga. Stay tuned for releases of these new software products.

Appendix A. Clustered-Event Hazard

The standard PSHA source is assumed to nucleate or occur independently of all other sources in the hazard model. There are known instances of sources that happen in a much more dependent manner, such as foreshock-mainshock-aftershock sequences. There are other cases of sources that are linked, in such a way that when one occurs, other mainshocks occur in a short time frame, usually within a few weeks or months of one another.

Hazard from events that are clustered in time and space is now computed using the code hazFXnga7c.f. The clustered-event option is selected by making the quantity that follows the spectral period a negative number. The absolute value of this negative number is an important integer, representing the number of groups of clustered events. Our model has groups representing different sub-parallel faults, or virtual faults, and within each group, our model has segments. We currently allow up to 5 groups, and 2 or 3 segments per group. A clustered event is the occurrence of two or three events on segments within a group.

Figure A1 shows the distribution of fault locations (red lines) as 5 groups and 3 segments that USGS is using in 2007 to describe seismic hazard from clustered events in the New Madrid Seismic Zone (NMSZ) along the Mississippi River (central U.S.). The three segments are labeled A, B, and C. The groups are the 5 zig-zagging faults, which are numbered 1 to 5, west to east. We do not know the magnitudes of future major earthquakes in this region, so we handle M-uncertainty by defining a set of scenarios. Each scenario is determined by assigning plausible magnitudes to the two or three ruptures on each virtual fault within a group. Software currently allows for up to 8 scenarios per group during a given run of hazFXnga7c.

NMSZ Clustered-event Fault Branches

GMT Jun 18 09:20   Numbers for groups, letters for segments. A=Northeast segment, B= Central segment, C= Southwest segment.
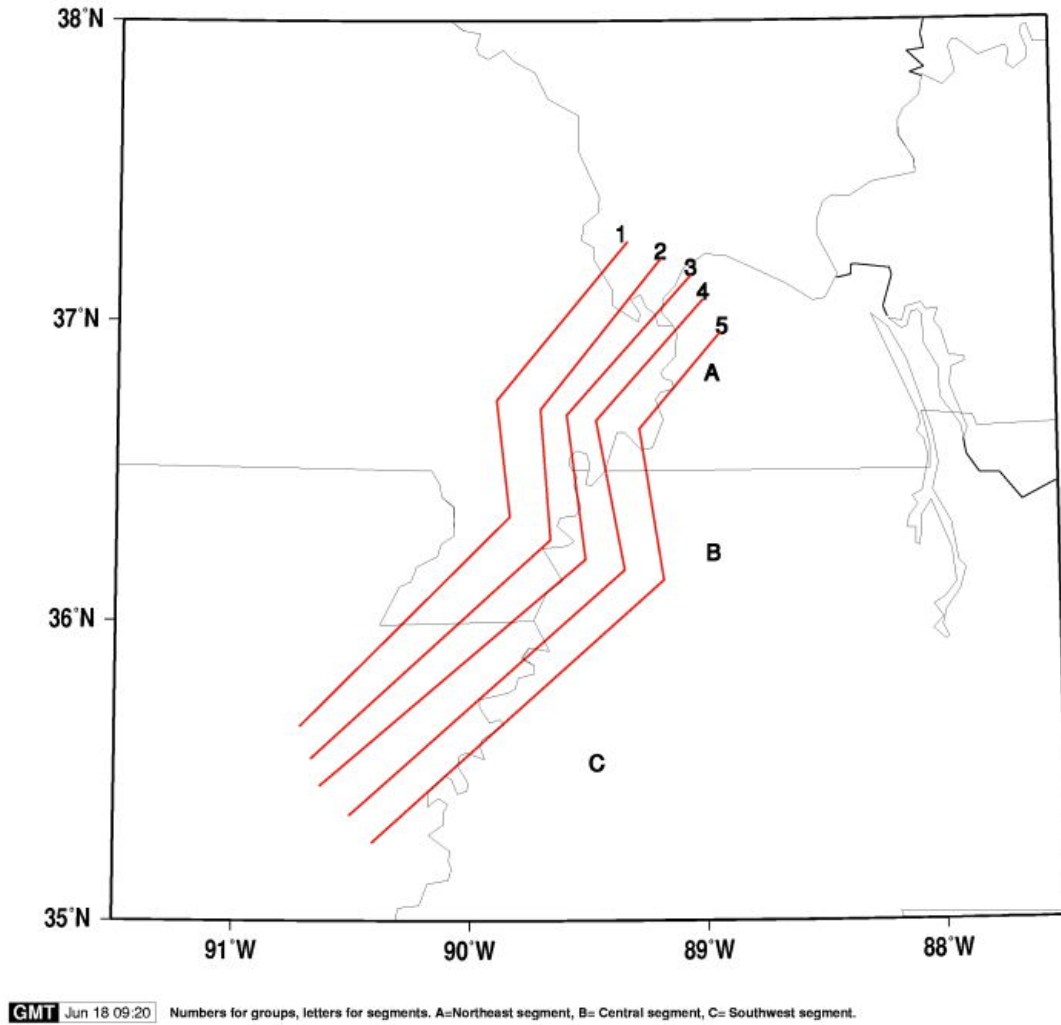
Figure A1. Geographic groups (numbers) and segments within a group (letters).

A fundamental grouping requirement is that every event in the clustered-event set must have the same mean repeat time, or recurrence rate, λ (which is 1/recurrence interval). The exceedance-rate equation is

$$R = \lambda\left[1 - (1 - P_1)(1 - P_2)(1 - P_3)\right],$$

(A1)

where P_1 is the probability of a ground-motion exceedance from the first source in the cluster, P_2 is the probability of exceedance from the second source, and P_3 is the probability of exceedance from the third source (such as sources A,B, and C in fig. A1), computed at a specific site and with specified M for each of these sources. This equation applies to any given triple of scenario events; the scenarios are then weighed by their likelihood and combined into the mean hazard estimate. A similar equation with n factors $(1-P_k)$ would be used for n clustered events, but this is not currently implemented in the software.

We build the scenarios and weights using spreadsheet tools. Spreadsheets are helpful for checking that the models are relatively complete and balanced, and that sums of scenario weights are correct. Currently we do not have a specialized source code for generating sets of scenarios.

The way that fault ruptures are clustered in the software is determined by a cluster-group index and a segment index for each event. This double indexing is done in the following clustered-event file used in the 2007 PSHA for the New Madrid Seismic zone. The lines with -5 (first one is blue) tell the program to cluster the events that will follow. The first red line below provides the information that the code needs for clustering ground motions from one segment and one group according to the above equation. This line has the sequence 1 1 4 1 1 in it. The first one says characteristic event, the next says, strike slip, the next says, 4 scenarios, the next says group 1 (western fault), and the next says segment 1 (north or A segment in figure A1). The next source below begins with the orange line with the number sequence 1 1 4 2 1, where all of the indexes have the same values except for the group number which is now 2 (Midwestern fault). Many more events are defined in this file, the last one being highlighted in brown, corresponding to scenarios for the 5th group (eastern fault) and the 3rd segment (south or C segment in figure A1).

Sample Input File for Clustered Events:

```
0               !500 year cluster; N, central, and S rupture of NMSZ
24.6 50. .1
-115. -65. .1           !ceus locations
760 1.
5. 1000.
3
0. -5. 0. PGA      !-5 means cluster model with 5 groups or branches
newmad-500-pga.clu
19
.005 .007 .0098 .0137 .0192 .0269 .0376 .0527 .0738 .103 .145 .203 .284
.397 .556 .778 1.09 1.52 2.13
8
2  0.2 10000. 0.2 0 Toro Mw atten.
6  0.1 10000. 0.1 0 FEA
4  0.1 10000. 0.1 0 AB06 140 bar stress drop
21 0.1 10000. 0.1 0 AB06 200 bar stress drop
7  0.2 10000. 0.2 0 Somerville Rifted, BC
10 0.1 10000. 0.1 0 Campbell hybrid, BC
19 0.1 10000. 0.1 0 Tavakoli and Pezeshk, BC
20 0.1 10000. 0.1 0 Silva
1.0 -5. 0.     1.0 sec SA
newmad-500-1hz.clu
20
.0025 .00375 .00563 .00844 .0127 .0190 .0285 .0427 .0641 .0961 .144
.216 .324 .487 .730 1.09 1.64 2.46 3.69 5.54
8
2  0.2 10000. 0.2 0 Toro Mw atten.
6  0.1 10000. 0.1 0 FEA
4  0.1 10000. 0.1 0 AB06 140 bar stress drop
21 0.1 10000. 0.1 0 AB06 200 bar stress drop
7  0.2 10000. 0.2 0 Somerville Rifted, BC
10 0.1 10000. 0.1 0 Campbell hybrid, BC
19 0.1 10000. 0.1 0 Tavakoli and Pezeshk, BC
20 0.1 10000. 0.1 0 Silva
0.2 -5. 0.   0.2 sec SA
newmad-500-5hz.clu
19
.005 .0075 0.0113 .0169 .0253 .0380 .0570 .0854 .128 .192 .288 .432
.649 .973 1.46 2.19 3.28 4.92 7.38
8
2  0.2 10000. 0.2 0 Toro Mw atten.
6  0.1 10000. 0.1 0 FEA
4  0.1 10000. 0.1 0 AB06 140 bar stress drop
21 0.1 10000. 0.1 0 AB06 200 bar stress drop
7  0.2 10000. 0.2 0 Somerville Rifted, BC
10 0.1 10000. 0.1 0 Campbell hybrid, BC
19 0.1 10000. 0.1 0 Tavakoli and Pezeshk, BC
20 0.1 10000. 0.1 0 Silva
1. 1.
1
0
1.
0.0 1 !start with no ale dM for the clustered-event calculations.
1 1  4 1 1  New Madrid western fault; North seg; 500 yr return time
7.1 0.002  0.00375
7.3 0.002  0.005
7.5 0.002  0.0125
```

```
7.8 0.002  0.00375
89. 15. 10.
2
37.263 -89.323
36.734 -89.886
1 1 4  2 1 New Madrid mid-western fault;
7.1 0.002 0.0075
7.3 0.002 0.01
7.5 0.002 0.025
7.8 0.002 0.0075
89. 15. 10.
2
37.205 -89.1814
36.704 -89.6991
1 1 4  3 1  New Madrid central fault;
7.1 0.002 0.0525
7.3 0.002 0.07
7.5 0.002 0.175
7.8 0.002 0.0525
89. 15. 10.
2
37.150 -89.053
36.686 -89.587
1 1  4  4 1 New Madrid mid-eastern fault;
7.1 0.002 0.0075
7.3 0.002 0.01
7.5 0.002 0.025
7.8 0.002 0.0075
89. 15. 10.
2
37.07 -89.001
36.667 -89.4625
1 1  4 5 1  New Madrid eastern fault;
7.1 0.002 0.00375
7.3 0.002 0.005
7.5 0.002 0.0125
7.8 0.002 0.0037
89. 15. 10.
2
36.960 -88.929
36.639 -89.279
1 1  4  1 2  New Madrid western fault; central seg.; 38d dip; 500 yr
return time
7.3 0.002  0.0075
7.5 0.002  0.010
7.7 0.002  0.025
8.0 0.002  0.0075
38. 15. 10.
2
36.734 -89.886
36.346 -89.830
1 1  4  2 2 New Madrid mid-western fault;
7.3 0.002 0.015
7.5 0.002 0.02
7.7 0.002 0.05
8.0 0.002 0.015
38. 15. 10.
```

```
2
36.704 -89.6991
36.27 -89.6575
1 1 4  3 2  New Madrid central fault;
7.3 0.002 0.105
7.5 0.002 0.14
7.7 0.002 0.35
8.0 0.002 0.105
38. 15. 10.
2
36.686 -89.587
36.205 -89.510
1 1  4  4 2 New Madrid mid-eastern fault;
7.3 0.002 0.015
7.5 0.002 0.02
7.7 0.002 0.05
8.0 0.002 0.015
38. 15. 10.
2
36.667 -89.4625
36.17 -89.344
1 1  4 5 2  New Madrid eastern fault;
7.3 0.002 0.0075
7.5 0.002 0.01
7.7 0.002 0.025
8.0 0.002 0.0075
38. 15. 10.
2
36.639 -89.279
36.135 -89.178
1 1  4  1 3 N. New Madrid western fault, S segment; 500 yr return time
7.3 0.002  0.0075
7.5 0.002  0.010
7.7 0.002  0.025
8.0 0.002  0.0075
89. 15. 10.
2
36.346 -89.830
35.647 -90.719
1 1  4  2 3 New Madrid mid-western fault;
7.3 0.002 0.015
7.5 0.002 0.02
7.7 0.002 0.05
8.0 0.002 0.015
89. 15. 10.
2
36.27 -89.6575
35.54 -90.6725
1 1 4  3 3  New Madrid central fault;
7.3 0.002 0.105
7.5 0.002 0.14
7.7 0.002 0.35
8.0 0.002 0.105
89. 15. 10.
2
36.205 -89.510
35.449 -90.633
```

```
1 1 4 4 3  New Madrid mid-eastern fault;
7.3 0.002 0.015
7.5 0.002 0.02
7.7 0.002 0.05
8.0 0.002 0.015
89. 15. 10.
2
36.17 -89.344
35.35 -90.51
1 1 4 5 3  New Madrid eastern fault;
7.3 0.002 0.0075
7.5 0.002 0.01
7.7 0.002 0.025
8.0 0.002 0.0075
89. 15. 10.
2
36.135 -89.178
35.260 -90.415
```

Output Files for Clustered Events:

The output files that *hazFXnga7c* writes for clustered events are distinguished by two features: (1) ".g1" or ".g2" … ".g5" is appended to the output file names to indicate which groups' hazard curves are included in that file, and (2), the header record also keeps tract of the group. These groups' hazard-curve data are kept separate because geographic uncertainty of source may be thought of as an epistemic alternative (rather than aleatory), because with further study and insight, the true location of the sources may one day be known. Often the earth scientist or engineer will want to look at epistemic alternatives in a logic-tree analysis. Logic-tree analysis is easier to do if the different alternative hazard curves are kept in separate files.

When combining the grouped hazard curves into the mean hazard it is necessary to know if the weights of the epistemic branches were applied in the input file to *hazFXnga7c* (they were in the above sample input file) or whether they are to be included in the input file to *hazallXL.v2*.f.

If you are studying response at *k* spectral periods and are considering *n* clustered-event groups, keep in mind that *hazFXnga7c* will write *kn* output files. Current source-code limits are $1 \leq k \leq 8$ and $1 \leq n \leq 5$.

Clustered-event hazard is the newest feature of *hazFXnga7c*, written in May 2007, and is the least explored feature as far as quality assurance is concerned. Our implementation is not as general as we would like. For example, you cannot include magnitude uncertainty, because in our way of balancing moment-rate, magnitude uncertainty produces frequency-of-event variability, but this is unacceptable according to equation A1. We have yet to find a suitable modification of the program to allow for M-uncertainty with clustering.

Appendix B: Frequently Asked Questions

How can I get ascii output? Often the output is binary and I can't read binary.

There are several ways to get ascii output.
effect, the first field in the input file of hazFXnga7c or whatever should be an integer n specifying the number of stations (up to 30) and the next n records should be station location information. The output will be ascii for each station.

(2) Run the binary output through the program hazallXL.v2 and specify ascii output in this run. This is typically what we do. This program can work with just one binary file, such as the output of hazFXnga7c.f, or can combine several output files' data, which is the standard use. When combining several, the same grid of sites must be computed, and the same set of SA levels or PGA levels must be used for all inputs. There is no interpolation so the X-values and sites have to match. It checks and if you don't have compatible files it will croak but will let you know why it croaked.

(3) Run the binary output through the program hazpoint. This program will output the hazard curve corresponding to the location you specify, for example 34. -116. This is a standard program used for checking various output files that are supposed to be the same. You can list several input files to look at the single-site hazard curves for. The input files do not need to be gridded the same, but the point of interest needs to be in each of them.

(4) A slight variation on 3 is to run hazpoint.v2. Here, you can combine several programs' output with specified weights and look at the curve or curves that result. You can group your files, for example, all of the A-faults in one group, all of the B-faults in the next, and so on. This is often helpful as a primitive deaggregation technique.

USGS Golden can supply sample input files and any of the above programs if they aren't in the zip file or folder where you might be expecting them.

Binary output of

hazgridXnga3 or …

Binary output of

hazgridFXnga7c

Binary output of

hazSUBXnga

hazallXL.v2
or
hazpoint
or
hazpoint.v2